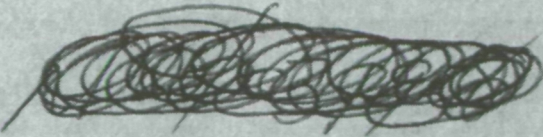


ANALYSIS OF SPACE TELESCOPE
DATA COLLECTION SYSTEMS

DEF 1



FINAL REPORT

NAS8-33570
July 1984



Submitted To:

George C. Marshall Space Flight Center
National Aeronautics and Space Administration



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<u>Part</u>	<u>Page</u>
I. INTRODUCTION	iii
II. ANALYSIS OF THE SPACE TELESCOPE MA	
LOW DATA RATE COMMUNICATION LINK	v
III. A REPORT CONCERNING PROPOSED ESTL TESTS	
AND POSSIBLE PROBLEMS ASSOCIATED WITH THE	
ENCODERS OF SPACE SHUTTLE	93
IV. A REPORT ON THE ESTL END-TO-END TESTS	114
V. MEMORANDUM CONCERNING SPACE TELESCOPE	
VERIFICATION REQUIREMENTS AND SPECIFICATION	
DOCUMENT (VRSD)	127

ANALYSIS OF SPACE TELESCOPE
DATA COLLECTION SYSTEM

I. INTRODUCTION

This final report consists of four parts other than the introduction:

PART II: describes the MA Low Data Rate Communication Systems and presents a detailed analysis of the expected system performance.

PART III: describes the rationale and make up of the proposed ESTL Tests as defined at the White Sands, NM, preliminary meeting. This is included for background information for Part IV.

PART IV: describes the ESTL Space Shuttle end-to-end tests and analysis of the results of the tests. Information the system performance of concatenated coding systems with a convolutional outer coder and a BCH inner coder was gained from these tests. This information was instrumental in the review of the Space Telescope Verification Requirements and Specifications Document (VRSD) of Part V. The suggestions put forth in the memorandum of Part V are a result of the insight into such concatenated coding systems as will be on the Space Shuttle and the Space Telescope vehicles.

PART V: describes the VRSD and offers some suggestions for the Space Telescope end-to-end testing procedure.

Finally it is worth noting that earlier Interim Final Reports on this contract are:

Report A: Analysis of Space Telescope Data Collect Information, July 31, 1982.

Report B: Analysis of Space Telescope Data Collection System, October 31, 1980.

The Interim Final Report A covers the basis of the Multiple Access (MA) link including encoded data expected bit error performance, an analysis of the false acceptance of a command word Due to Data Version on the UpLink for commands, and a summary of the S-Band Single Access System (SSA) analysis.

The Interim Final Report B covers the detailed analysis of the Single Access System including the concatenated Reed/Solomon Convolutional encoding scheme to be used on Space Telescope. It is a fully comprehensive report including anticipated effects of RFI on the SSA Science Data Link.

The three report volume, this Final Report (1984) and the Interim Final Reports (1982) and (1980) comprise a fully comprehensive tutorial, analysis and predicted performance of the MA and SSA Links to be used on the Space Telescope and a discussion of many ancillary points of these systems and of the proposed VRSD for Space Telescope. They are recommended reading for any engineer/manager working on the Space Telescope project in so far as the science data and engineering data communication links are required.

Copies of these reports are available from NASA; Marshall Space Flight Center; Huntsville, AL.

II. ANALYSIS OF THE SPACE TELESCOPE MA LOW DATA RATE COMMUNICATION LINK

This section is a tutorial and analysis of the MA communication link of the Space Telescope System. An expected performance bit error rate analysis is presented and recommendations are given in Section 4.0.

TABLE OF CONTENTS

Chapter		Page
	LIST OF FIGURES	ix
	LIST OF TABLES	x
	LIST OF SYMBOLS	xi
1	INTRODUCTION	
	1.A Command Function and Forward Communication from Goddard to the Space Telescope Spacecraft	1
	1.B Data Function	6
	1.B.1 Engineering Data	6
	1.B.2 Engineering Data Subsystem	6
	1.B.3 Science Data	7
	1.C Return Communication Links	8
2	THE SPACE TELESCOPE MULTIPLE ACCESS SYSTEM . . .	14
	2.A Space Telescope Orbiting Observatory	14
	2.A.1 Scientific Instruments	15
	2.A.2 Control Unit/Science Data Formatter	15
	2.A.2.a Data Interface Unit	17
	2.A.2.b Master Oscillator	17
	2.A.2.c Optical Telescope Assembly	17
	2.A.3 Engineering Data Coding	19

TABLE OF CONTENTS (Continued)

Chapter		Page
	2.A.4 Support System Module	19
	2.A.4.a Data Management Sub- system	19
	2.A.4.b Instrumentation and Communications System (SSA Link)	
	2.A.4.c Instrumentation and Com- munications System II (MA Link)	31
	2.B Tracking and Data Relay Satellite System	32
	2.B.1 Return Channel Link Model	32
	2.B.2 Ground Station	33
	2.C NASA Communications Network	37
	2.D Assumptions	38
3	ANALYSIS OF THE PERFORMANCE OF THE MA RETURN LINK	39
	3.A Probability of Error on the Inner Channel .	39
	3.A.1 Transition Density	39
	3.A.2 Tape Recorders	44
	3.A.3 Synchronization	44
	3.A.4 Multiple Frame Format Operation	47
	3.A.5 Radio Frequency Interference	47
	3.A.6 SQPN Modulation	53

TABLE OF CONTENTS (Continued)

Chapter		Page
	3.A.7 Use of Identical Phase Shifted PN Codes on the I and Q Channels . . .	53
	3.B MA Self-Interference	53
	3.C Flux Density Affect on MA Return Link	56
4	RECOMMENDATIONS AND RESULTS	
	APPENDICES	67
	A Example of Reed/Solomon Encoder/ Interleaver	68
	B Delay Modulation (Miller Complement)	72
	C Example of a Concatenated Code	77
	D Affect of PSK Demodulator Carrier Slip on Differential Encoded Data With/Without Interleaving	82
	E Multiple Access Self-Interference	86
	REFERENCES	91

LIST OF FIGURES

Figure	Page
1.1 The Space Telescope System	2
1.2 Command Formats (a) DMS and (b) Si C&DH	4
1.3.A ST Data Transmission Flow	9
1.3.B ST MA and Cross Support Link Configurations	
2.1 Engineering Data Flow Through the ST	16
2.2 Command Requirements for the MA Link	20
2.3 Differential Encoder With Truth Table	25
2.4 Convolutional Encoder With Cover Sequence	27
2.5 Convolutional Encoder With PCI and Cover Sequence	29
2.6 Periodic Convolutional Interleaver and Deinterleaver	30
2.7 Synchronization Strategy for the Periodic Convolutional Deinterleaver	36
3.1 General ST/TDRSS Concatenated Coding Concepts	40
3.2 Costas Loop	48
3.3 MA Self-Interference Degradation	55
4.1 Concatenated Coding BER Versus TDRSS Channel Viterbi Decoded BER for R/S ($\tau = 8$)	65
4.2 Error Rate Performance of K = 7, R = 1/2 System With Satellite RFI Blanking	66
B.1 NRZ-L and Delay Modulation Binary Signal Waveforms	74
C.1 Concatenated Codes	79

LIST OF TABLES

Table	Page
3.1 Data Loss Estimates Due to Sync Loss	46
3.2 Expected Bit Error Rate for the MA Link Due to RFI and Bit Slip	58
4.1 TDRSS EIRP Requirements for the MA Return Link	
4.2 MA Predicted Performance	62
E.1 Interference Model No. 1A	89
E.2 Interference Model No. 1B	89
E.3 Interference Model No. 1C	90
E.4 Interference Model No. 1D	90

LIST OF SYMBOLS

BER	Bit Error Rate
BCU	Bus Coupler Unit
BPSK	Bi-phase Shift Keying
BSR	Bit Slip Rate
CCIR	International Radio Consultative Committee
CDI	Command Detector Interface
C.E.	Convolutional Encoder
CU/SDF	Control Unit/Science Data Formatter
DIU	Data Interface Unit
DMS	Data Management Subsystem
DMU	Data Management Unit
DOMSAT	Domestic Satellite System
E	Number of Correctable Symbol Errors per R/S Block
EIRP	Effective Isotropic Radiated Power
ESTR	Engineering/Science Tape Recorders
TGS	Fine Guidance Sensor
GSFC	Goddard Space Flight Center
HGA	High Gain Antenna
Hz	Hertz
I	In-phase
IC	Integrated Circuits
I&C	Instrumentation and Communications Subsystem

LIST OF SYMBOLS (Continued)

J	Number of Bits Per R/S Symbol
Kbps	Kilobits Per Second
LGA	Low Gain Antenna
MA	Multiple Access
Mbps	Megabits Per Second
MDB	Multiplexed Data Bus
MHz	Megahertz
MSB	Most Significant Bit
N_{\max}	Maximum Number of Output Symbols of the Convolutional Encoder w/o a Transition
NASCOM	NASA Communications Network
NRZ-L	Non-Return-to-Zero-Level
NSSC-I	NASA Standard Spacecraft Computer, Model I
OTA	Optical Telescope Assembly
$P_1(E)$	The R/S Input Symbol Error Probability
$P_2(E)$	The Output Probability of the R/S Decoder/Deinterleaver
$P_b(E)$	Probability of a Bit Error Occurring on the Inner Channel
$P_b(E)$	Average Bit Error Rate of the DOMSAT Link
$P_{R/S}(E)$	Symbol Error Probability Out Of The R/S Decoder Deinterleaver
$P_T(e)$	Overall Bit Error Probability
$P_{VD}(E)$	Bit Error Rate Out of the Viterbi Decoder
$P_{WS}(E)$	Average Bit Error Rate of the TDRSS Link
PCI	Periodic Convolutional Interleaver
PCU	Power Control Unit

LIST OF SYMBOLS (Continued)

PIT	Processor Interface Table
PN	Pseudo Noise
PSK	Phase Shift Key
Q	Quadrature-phase
QPSK	Quadrature-phase Shift Keying
RF	Radio Frequency
RFI	Radio Frequency Interference
RM	Remote Module, Resource Monitor
R/S	Reed-Solomon
SDF	Science Data Formatter
SI	Scientific Instrument
SI C&DH	SI Control and Data Handling (Subsystem)
SNR	Signal to Noise Ratio
SSA	S-band Single Access
SSM	Support Systems Module
ST	Space Telescope Orbiting Observatory
STINT	Standard Interface for Computer
STOCC	Space Telescope Operations Control Center (at GSFC)
ST Sci	Space Telescope Science Institute Contractor
T	Interval of Heavy RFI
TDRSS	Tracking and Data Relay Satellite
TDRSS	Tracking and Data Relay Satellite System
VCO	Voltage Control Oscillator

CHAPTER 1

INTRODUCTION

1.A Command Function and Forward Communication From Goddard to the Space Telescope Spacecraft.

The Space Telescope System's primary objective is to develop and operate a large high quality optical telescope in low earth orbit and to provide an astronomical laboratory capability beyond the reach of earth based observatories. The Space Telescope System consists of the Space Telescope Orbiting Observatory (ST), the Space Telescope Science Institute (ST ScI), and the Space Telescope Operations Control Center (STOCC). The Space Telescope System, Figure 1.1, will be supported by the Space Shuttle, the Tracking and Delay Relay Satellite System (TDRSS), and the NASA Communications Network (NASCOM). The remainder of this section is a summary of the end-to-end ST data system.

The objective is to provide a brief description of the major ST data originators and/or recipients and to show aspects of the system that interact with the data. The intent is to illustrate how the data is generated, how it is related to the ST system and to explain pertinent data manipulations and unique ST characteristics that influence the system.

The planning and scheduling of ST missions is the responsibility of the ST ScI and the STOCC. The ST ScI's primary function is

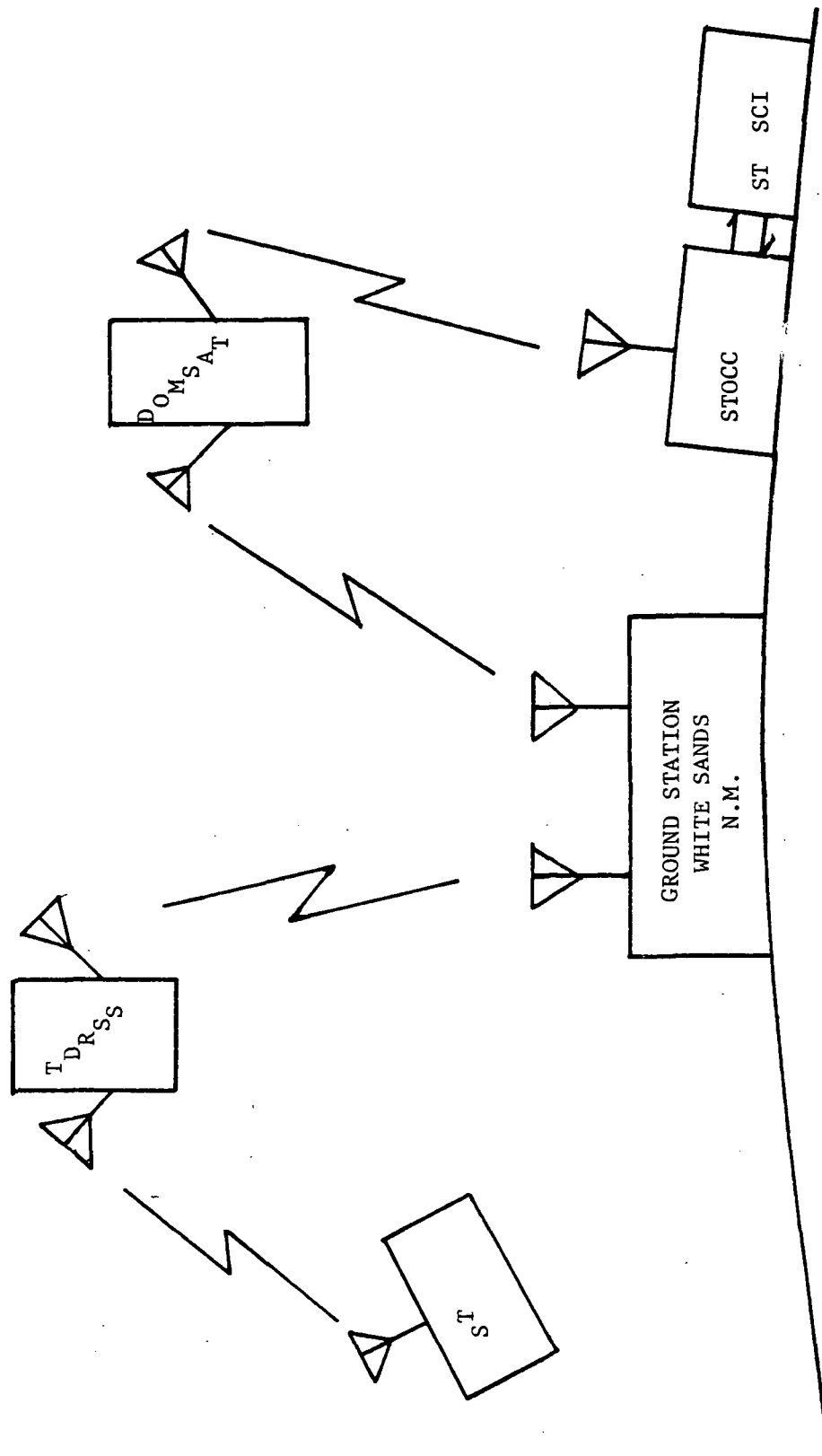


Figure 1.1. The Space Telescope System.

to evaluate and select proposals from the scientific community and implement the selected proposals into a monthly science plan based on various constraints to receive maximum utilization of the ST. This monthly science plan is sent to STOCC where it is converted into orbit-by-orbit sequences. The STOCC is the primary and central controlling facility for performing ST mission operations.

The execution of the desired scientific observation and operations required to maintain the ST are accomplished by the command function. The command function includes the generation, loading, verification, and execution of both real-time and stored program commands. The STOCC is responsible for the issuing of both science related commands from the daily science schedule and spacecraft related commands.

Commands are generated by the Command Management System. This system consists of off-line routines which provide for the generation of planned real-time and stored program commands, software updates to the DF 244 and NSSCI computers, and data updates. The scheduled uplinks to the ST are formatted into 48 bit command words in the off-line system. The first seven bits are the spacecraft address and the last seven bits are an error protection Hamming code which is inserted prior to transmission by the on-line system. Uplinks are assembled as single commands or in blocks up to 256 words each, Figure 1.2. The single commands are realtime, and the blocks are stored program load or data updates. The first word in each block provides memory starting address and block length for stored program commands and software updates. A data block or table number

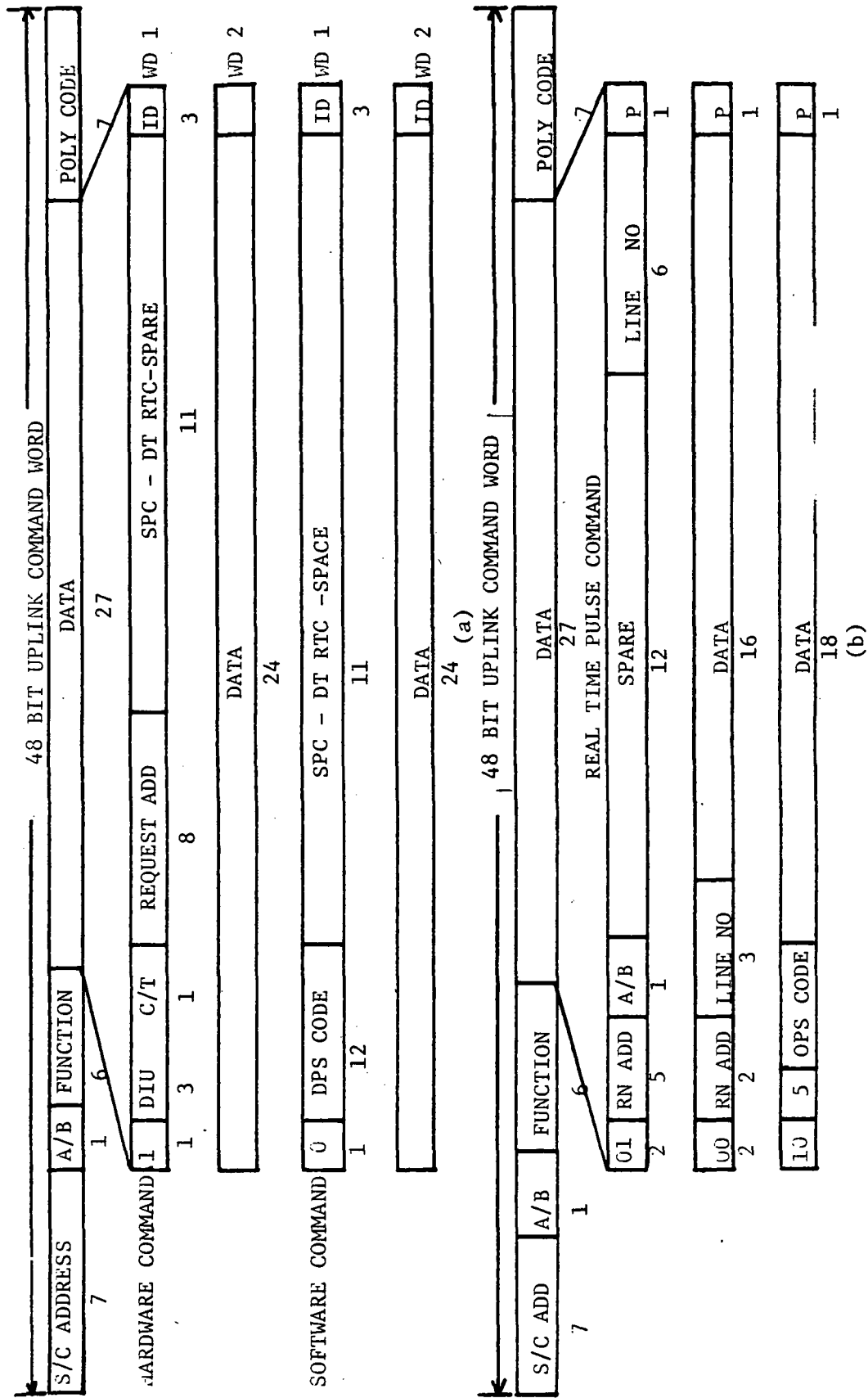


Figure 1.2. Command Formats (a) DMS and (b) SI CSDH.

is used to replace memory locations in data updates. The ground computed checksum is contained in the last word of each block.

Each uplink is preceded by an acquisition sequence at 0.125 Kbps or 1.0 Kbps generated by the transponder command detector unit. Each command block is preceded by a 48-bit Command Data Interface (CDI) synchronization word. The standard 4800-bit NASCOM block format is used for all command words. Once up-link loc and data synchronization has been established, the CDI decodes the Hamming code, performs a valid bit count on each command word decodes the address, and routes valid commands. Special commands are routed directly to the designated recipient. All other commands are routed to the Data Management Subsystem (DMS) for distribution. The commands for the Support System Module (SSM) are transmitted to the DF 224 computer and the Scientific Instruments Control and Data Handling (SI C&DH) system commands are transmitted to the Control Unit/Science Data Formatter (CU/SDF). Stored program commands are stored in temporary buffer until the last word in a block is received and then the entire block is transferred to memory.

Control and routing of commands is handled by the DMS. The DMS outputs commands via a Data Interface Unit (DIU) to the users or for special commands direct from DMS decoder to user. A 27-bit serial magnitude command interface is used to route SI C&DH commands to the CU/SDF. Real-time commands are received at either a 20.83 or 2.60 per second rate.

1.B Data Function

1.B.1 Engineering Data

All ST data is routed to the Support System Module (SSM) where it is collected, recorded and/or transmitted to the STOCC. The data originating in the ST are grouped into two categories, engineering data and science data. Engineering data contains information on the performance and functional operation of the ST elements. Engineering data from the Scientific Instruments (SI) and the SI C&DH are collected by the CU/SDF and routed to the DIU as a composite data stream. Engineering data is routed to the Data Management Unit (DMU) via DIU. The SSM and the Optical Telescope Assembly (OTA) engineering data are combined with the SI and SI C&DH engineering data to form the composite ST engineering data rates of 0.5, 1.0, 4.0, 8.0, or 32 Kbps.

The DMU arranges the data into major frames which consist of 120 or 20 minor frames. Each minor frame contains either 250 or 125 eight bit words and a 24-bit frame synchronization word. The DMU is capable of collecting and formatting the data in one of the five formats, three of which are programmable by software control and two of which are fixed by hardware control. The data are transferred to the Multiple Access (MA) system for real-time transmittal to the STOCC or to the engineering tape recorder for later transmission. The 0.5 Kbps data rate is utilized for real-time transmission only.

1.B.2 Engineering Data Subsystem

The engineering data is arranged in minor frames which are either 1000 or 2000 bits in length.

Each minor frame has a 24 bit frame synchronization word placed at the beginning of the minor frame. These minor frames obtained from the elementary bit stream are referred to as engineering data.

The engineering data rates are either .5, 1, 4, 8, 32 Kbps. The 4 Kbps are upconverted prior to onbound recording to eight times the incoming rate by segmenting each bit into eight subbits. An input bit of one is converted to a pattern of 10010111 and an input bit of zero is converted into a pattern of 10010000. These patterns were picked because they have good error protection properties using Miller Code for direct recording on the engineering tape recorder. The 32 Kbps data is not upconverted.

All the engineering data entering the high data rate telemetry system is recorded on tape. The tape recorder playback rate is adjusted to result in a 1.024 Mbps output data rate.

1.B.3 Science Data

The science data contains the observational output of one or more of the five scientific instruments (SI). The science data is routed directly from the SI or from the NASA Standard Spacecraft Computer, Model I (NSSCI) to the DMU via the CU/SDF. The CU/SDF collects and formats the data into segments of 1024 bits. Each segment contains a 24 bit synchronization pattern, an 8 bit segment number and a 16 bit packet count. These segments are grouped into packets, each packet contains the ancillary identification information. Normally a packet contains a complete line of science data from only one SI, however, packets from two different SI may be combined and transferred to the DMU as a composite science

data stream. The CU/SDF contains a Reed/Solomon (R/S) encoder which is utilized to concatenate an outer error correcting code with the science data. The R/S encoder is constructed in such a manner that the data word parity checks are interleaved, although the information words themselves are sent unaltered. The R/S encoder is utilized to give immunity to TDRSS channel degradation and to protect against burst errors. The science data are transferred to the DMU at 4.0, 32.0, or 1024 Kbps rate for transmission in real-time to STOC and for recording for later transmission. The 4.0 Kbps data rate utilizes the MA system and the 1.024 Mbps utilizes the S-band Single-Access (SSA) system for real-time transmission. The 32.0 Kbps data rate is for tape recording only.

The DMU is a component of the Data Management System (DMS). The DMS, also, includes three identical magnetic tape recorders. One is allocated to the engineering data and one to the science data with the third as a spare, which may be deleted. The tape recorders are capable of recording data at rates of 32.0, 64.0 or 1024 Kbps. The science data and engineering data rates of 4.0 and 8.0 Kbps are up-converted to 32.0 and 64.0 Kbps respectively by an 8 bit pattern, prior to being recorded. Data rates of 32.0 and 1024 Kbps are recorded at their data rates. All data rates are played back at a 1.024 Mbps rate and in reverse. The tape is not rewound prior to playback, creating a need for reversible sync pattern on the tape.

1.C Return Communication Links

All ST data are transmitted to STOC via the TDRSS and NASCOM utilizing the MA and SSA systems. Figure 1.3A illustrates the

end-to-end ST data transmission flow. The MA system is utilized to transmit real-time engineering data at 0.5, 1.0, 4.0, 8.0, or 32.0 Kbps and science data at 4.0 Kbps. The ST MA and cross support return link configuration are shown in Figure 1.3.B. Except for the 0.5 Kbps data rate, the data are transmitted to the TDRSS utilizing the transmitter portion of the transponder via the high gain antenna (HGA) system. The 0.5 Kbps data rate is transmitted in the same way except via either the HGA or the low gain antenna (LGA) system. The MA return link utilizes two simultaneous, independent channels employing spread spectrum techniques. The TDRSS will provide the capability for 20 MA return link services, with each TDRS (including the in-orbit spare) capable of supporting all 20 MA return links. MA return link service will be dedicated to a user and can provide support for the entire portion of the user's orbit which is visible to at least one of the two operational satellites. All MA users will operate at the same frequency and polarization, and will be discriminated by unique PN codes and antenna beam pointing. Each channel is 1/2 convolutionally encoded and modulo-2 added to a PN code, which is unique for the ST, prior to modulating quadrature phases of a 2287.5 MHz 5 watt RF carrier. Either the In-phase (I) or the Quadrature-phase (Q) channel may be used to transmit engineering data at one of the above rates or both channels at the same rate. Only the I channel may be used to transmit the 4.0 Kbps science data. The data is despread, bit synchronized, and convolutionally decoded by the TDRSS ground station at White Sands, New Mexico. The ground station

Figure 1.3B. ST MA and Cross Support Return Link Configurations.

ST 2287.5 MHz RETURN LINK									
CONFIGURATIONS	TDRSS			ST		DATA RATE (kbps) AND TYPE			
	SERVICE	DG	MODE	ANTENNA	ANTENNA	I CHANNEL	Q CHANNEL		
R1A	MA	1	1	MA	HGA	0.5 ENGINEERING	0.5 ENGINEERING		
R1B	CROSS	1	1	SSA	LGA	0.5 ENGINEERING	0.5 ENGINEERING		
R1C	CROSS	1	1	SSA	HGA	0.5 ENGINEERING	0.5 ENGINEERING		
R2A	MA	1	1 or 2	MA	HGA	4.0 ENGINEERING	4.0 ENGINEERING		
R2B	CROSS	1	1 or 2	SSA	HGA	4.0 ENGINEERING	4.0 ENGINEERING		
R2C	CROSS	1	3	SSA	HGA	32.0 ENGINEERING	32.0 ENGINEERING		
R3A	MA	1	1 or 2	MA	HGA	4.0 SCIENCE	4.0 ENGINEERING		
R3B	CROSS	1	1 or 2	SSA	HGA	4.0 SCIENCE	4.0 ENGINEERING		
R2C	CROSS	1	1 or 2	SSA	HGA	4.0 SCIENCE	32.0 ENGINEERING		
R4A	CROSS	1	1 or 2	SSA	HGA	32.0 SSM MEMORY DUMP	4.0 ENGINEERING		
R4B	CROSS	1	3	SSA	HGA	32.0 SSM MEMORY DUMP	32.0 ENGINEERING		

- NOTES: 1. RANGING IS SCHEDULEABLE FOR ALL CONFIGURATIONS EXCEPT DG1 MODE 2.
2. DOPPLER MEASUREMENT IS SCHEDULEABLE FOR ST 1 & C CONFIGURATIONS R2A THROUGH R4B.
3. EITHER I OR Q CHANNEL MAY BE UNMODULATED.

also provides individual bit-contiguous data streams at the MA transmitter input rate to NASCOM.

The SSA system is utilized to transmit real-time Reed/Solomon Encoded science data at 1.024 Mbps and playback tape recorder data, both engineering and science, to the TDRSS via HGA system (the tape recorder data is not Reed/Solomon encoded, however). The data are differentially encoded, 1/3 rate convolutionally encoded, PN coded, and optimally periodic convolutionally interleaved during high RFI periods prior to BPSK modulating a 2255.5 MHz 14 watt RF carrier. The data stream is demodulated, bit synchronized, periodic convolutionally deinterleaved, and Viterbi decoded by the TDRSS ground station. The ground station provides an individual bit contiguous data stream at the SSA transmitter input rate to NASCOM.

The NASCOM terminal accepts the bit-contiguous data stream, formats the data into discrete 4800-bit NASCOM blocks. The 4800-bit blocks are time division multiplexed with other data blocks for transmission to Goddard Space Flight Center (GSFC) via common carrier. Prior to transmission each block is appended with an error detection code. The blocks of data are demultiplexed and checked for transmission errors at the GSFC terminal. The data blocks are then routed to the STOCC. The SSA system will utilize the Domestic-Communication Satellite (DOMSAT).

The Space Telescope System must provide a bit error rate (BER) of one error in 10^6 bits on the SSA system to obtain most of its main objectives for the current complement of SI's per Dr. D. S. Leckrone's

memo of January 26, 1978 to Mr. G. M. Levin. A BER of 2.5×10^{-5} is acceptable for the engineering data. The TDRSS will provide a western union guaranteed BER of 10^{-5} provided that the required effective isotropic radiated power (EIRP), measured in DBW, and the signal structure conditions are met by the user's signal. DOMSAT link will provide a BER of 10^{-7} . Under these conditions, the DOMSAT link will be viewed as transparent adding essentially no additional noise to the TDRSS BER of 10^{-5} .

In summary, the engineering data may be 1/2 convolutionally encoded and transmitted over the MA RF link or may be rate 1/3 convolutionally encoded, interleaved and transmitted over the SSA RF link. Since the rate 1/3 coding and interleaving is more effective in combatting errors and the SSA RF link has a higher signal-to-noise ratio, this link provides a lower overall bit error rate for the engineering data than does use of the MA RF link.

The next section is a more comprehensive description of the MA system. This section will discuss in detail the portion of the MA system on board the ST, the channel characteristics, and the expected overall performance.

CHAPTER 2

THE SPACE TELESCOPE MULTIPLE ACCESS SYSTEM

The objective of this section is to provide a more in depth view of the MA system. The MA system may be separated into three main subgroups for discussion purposes. The ST, the Return Link from the ST via TDRSS to White Sands, and from White Sands via DOMSAT to the STOC at GSFC. The ST is presently in the design and fabrication stage and is scheduled to be operational in the early part of Fall of 1983. The TDRSS is in a similar situation. Its operation date was originally November of 1980, but the date has been delayed to 1984. Therefore, several assumptions concerning the MA system must be made. These assumptions are described in the following paragraphs and listed at the end of this section.

2.A Space Telescope Orbiting Observatory

First, the portion of the MA system that is contained on board the ST will be discussed. This portion consists of the following main groups:

1. Support System Module (SSM).
2. Scientific Instrument Control and Data Handling (SIC&DH).
3. Scientific Instruments (SI).

Only the portions of these main groups which pertain to the MA Link will be discussed. Further information concerning the overall ST may be found in Reference 1.

2.A.1 Scientific Instruments

This section will consist mainly of tracking the flow of engineering data through the ST Figure 2.1. The engineering data originates from one of the Scientific Instruments, the Optical Telescope Assembly (OTA), and the Support System Module. The original complement of SI's consist of two imagery cameras, two spectrographs, a photometer and one of the three Fine Guidance Sensors (FGS). Each of the SI's has its own data format and data rate, but the format must be compatible with the science data format generated by the Control Unit/Science Data Formatter (CU/SDF). The data for the SI's are considered to be digitized data. For this reason, the SI and SIC&DH Engineering Data are routed from the SI's to the Control Unit/Science Data Formatter (CU/SDF), along with OTA Engineering Data and SSM Engineering Data to the (DIU) (Data Interface Unit).

2.A.2 Control Unit/Science Data Formatter

The SIC&DH is the interface between the SI's and the Support System Module (SSM). The SIC&DH receives, decodes, and stores and/or routes commands for the various SI's. The SIC&DH collects engineering and science data from the SI, processes this data, and transfers it to the SSM. Processing for the engineering data includes formatting suitable data for transmission and adding the outer error correcting code. The SIC&DH provides a general computing capability to support SI control, monitoring, and data manipulation/analysis. The SIC&DH includes the following components:

1. Control Unit/Science Data Formatter (CU/SDF)

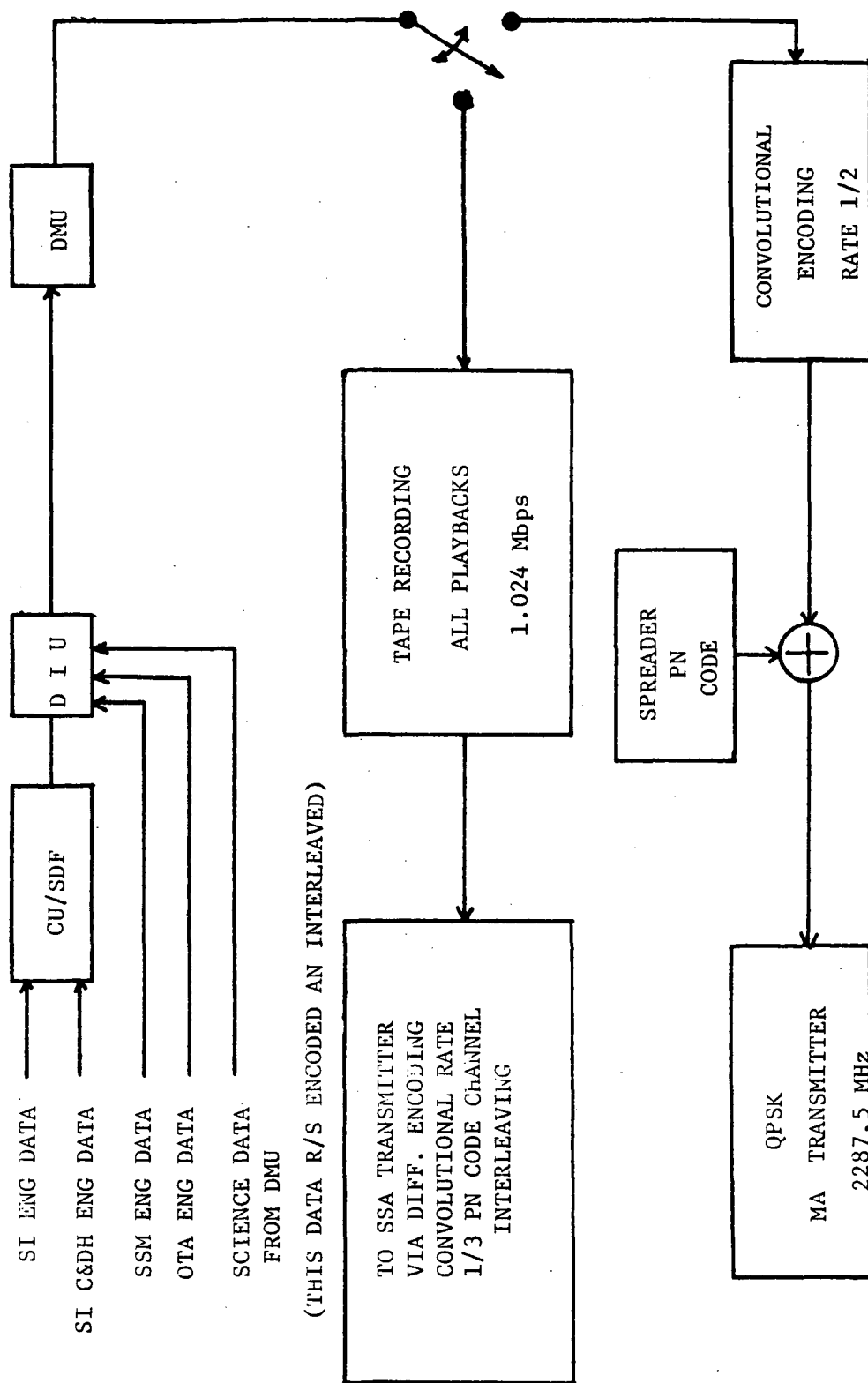


Figure 2.1. Eng. Data Flow Through the ST.

2. Multiplexed Data Bus (MDB).
3. Bus Coupler Unit (BCU).
4. Remote Module (RM).
5. Standard Interface for Computer (STINT).
6. NASA Standard Spacecraft Computer, Model I (NSSCI).
7. Power Control Unit.

2.A.2.a Data Interface Unit

The Data Interface Units (DIU) provides an interface between the DMU and various ST system users to provide the capability for decoding and issuing of commands and the collection of computer and telemetry data. The DIU's output power, serial digital commands and collect and process bi-level, analog, and serial digital telemetry signals. All DIU's are redundant and cross-strapped.

2.A.2.b Master Oscillator

The master oscillator is a temperature controlled, crystal oscillator that provides the basic clock signals for the ST. There are two oscillators cross-strapped so that either oscillator supplies clock signals to either DMU and to the SIC&DH. Each oscillator produces highly stable 6.144 MHz sine waves that are relatable to all ST clock signals.

2.A.2.c Optical Telescope Assembly

The OTA is a 2.4 mb 24 cassegrain telescope consisting of two elements, a primary and secondary mirror. The usable field of view of the telescope is 14 arc minutes half angle. The telescope

is designed such that the static on axis image quality of the useful image surface is no worse than $.075 \lambda$ ($\lambda = 6328\text{\AA}$) under orbital operating conditions.

The focal plane of the telescope is divided among eleven sensing devices; four axial scientific instruments, three optical control sensors, one radial scientific instrument and three fine guidance sensors. All of the focal plane sensors are in-orbit replaceable.

Each of the three fine guidance sensors contain the optical control interferometric wavefront quality sensor used to measure optical quality and telescope focus errors. The secondary mirror position is adjustable in orbit for tip, lift, decenter and descope. The primary mirror contains push-puff actuators to correct the shape of the primary mirror surface in orbit. The system of actuators is controlled from the STOC based on an analysis of the optical control subsystem data.

The temperature of the primary and secondary mirrors, the focal plane structure and the main ring attach points are all actively temperature controlled. The metering truss which separates the primary and secondary mirrors, is passively controlled.

The majority of the OTA electronic components are located in an OTA equipment section which mounts to the exterior of the SSM Equipment Section. All of the OTA electronic components in the OTA Equipment Section are in-orbit replaceable.

2.A.3 Engineering Data Coding

All spacecraft engineering data shall be maintained in temporary storage for 48 hours (TBR) or longer. If authorized by the ST mission Operations Manager with concurrence of all ST elements, data will be destroyed on a first-in-first-out basis, unless otherwise directed. Command requirements are shown in Figure 2.2.

Preliminary engineering data lists have been prepared. Although the specific data to be monitored is (TBD), a listing of the currently planned available data is provided. The data has the following coding:

TT	Type
SS	Source
DD	Destination
NN	Serial Number
BB	Bits With Words
II	Identification

2.A.4 Support System Module

The Data, including Science Data and R/S parity checks, is transferred to the SSM from the SIC&DH. The two subgroups of the SSM of interest are the Instrumentation and Communications Subsystem (I&C) and the Data Management Subsystem (DMS). The DMS will be discussed first, since this is the point at which the data will enter the SSM.

2.A.4.a Data Management Subsystem

The DMS is responsible for providing the acquisition, processing, storage, and dissemination of all data, including science

A. Discrete Commands (1 word).

No. of Bits Function in Command	7		1		6		3		1		2		2		16		1		2		7	
	S/C Address		A B		Function		DJU ADD		C D		DIU EXP		CPXI CHAN.		COMMAND DATA		P		SPARE		POLY CODE	

B. Serial Magnitudes 2 (words).

1. Hardware	7		1	6	1	3	1	8	11		3	7
Word 1	Address S/C		A	Function B		DJU 1		C	Request Address	Dt (if Store Command) Spare IF(RTC)	ID	POLY CODE
	14								24		3	7
Word 2	As in Word 1								DATA		ID	POLY CODE

C. Software (DF-224 CMD).

Word 1	7							12							11							7						
	S/C Address		A B		Function		0		QPS Code		Dt (if Stored) Spare (if RTC)		ID		POLY CODE		POLY CODE		POLY CODE		POLY CODE		POLY CODE		POLY CODE		POLY CODE	
Word 2	14																											
Word 2	S/C Address		A B		Function				Data		ID		POLY CODE		POLY CODE		POLY CODE		POLY CODE		POLY CODE		POLY CODE		POLY CODE		POLY CODE	

Figure 2.2. Command Requirements for the MA Link.

data between the ST communications and other subsystems. The DMS consists of the following components:

1. Data Management Unit (DMU),
2. DF 244 Computer,
3. Command Data Interface (CDI),
4. Tape Recorders,
5. Master Oscillator, and
6. Data Interface Unit (DIU).

Data Management Unit -- The DMU receives the data and clock signals from the SIC&DH at rates of 4.0, 32.0 or 1024 Kbps and routes the signals to the engineering tape recorder and/or the I&C for transmission. The 32.0 Kbps data rate is routed to the science tape recorder only. The 4.0 Kbps data rate is routed to the MA System, for transmission to the ground in Real Time, or it is up-converted to 32.0 Kbps and routed to the science tape recorder to be stored for transmission via the SSA system at a later time. The 1.024 Mbps data is routed either to the science tape recorder for direct recording for later transmission via the SSA system, or processed for Real-Time Transmission via the SSA system.

The Tape Recorders, engineering and science, are played back at the 1.024 Mbps data rate only, regardless of the record rate. For this reason, the playback science data will be included in the discussion of the MA system.

The 1.024 Mbps data rate, whether playback engineering data, playback or Real-Time Science Data, is processed by the DMU prior to transmission to the I&C. The signal processing function

includes a differential encoder, 1/3 Rate Convolutional encoder, a PN encoder and a Periodic Convolutional Interleaver.

Tape Recorders -- The DMS includes three identical tape recorders, one for the engineering, one for the science data, and one spare; which may be deleted to save cost. Both engineering and science data may be stored by any one tape recorder should the need arise. Each of the three Engineering/Science Tape Recorders (ESTR) contains 2000 feet of tape, has a maximum record/playback speed of 41 inches per second, and requires 30 seconds to reach this speed when used for 1.024 Mbps rate data. Each has a recording density of 25K bits per inch. The ESTR will be recorded at one of three rates, 32, 64, or 1024 Kbps. All recorded data is read out at a 1.024 Mbps rate only and in reverse, the tape is not rewound prior to read out. The reverse read out creates several problems. These problems are discussed in the following paragraph.

The ESTR will not accept data for recording until lock-on speed has been achieved and acknowledged by the tape. The time interval required to achieve lock-on will depend on the record rate used. The tape run during this time is referred to as preamble. The preamble will vary in length directly with the record rate. Assuming linear acceleration, 5 feet of preamble is required for the 1.024 Mbps rate. The reverse play back of all recorded data at 1.024 Mbps rate requires 5 feet of preamble and post-amble per input and data stream to the ESTR. The 5 feet of post/preamble has not been incorporated into the system to date. The Engineering/Science Tape Recorder (ESTR) accepts data rates of 4.0, 8.0, 32.0 and 1024 Kbps. Prior to recording, the 4.0 and 8.0 Kbps data are upconverted by an

8-bit sequence to 32 and 64 Kbps rates, respectively. In addition, the NRZ-L input format is converted to a Delay Modulation or Miller Complement Code for the purpose of improving the high density digital recording process. The conversion results in a phase ambiguity condition which results in logic states being inadvertently complemented (i.e. "1" becomes "0" and vice versa) when the data is converted back to NRZ-L prior to being read out of the ESTR. A brief discussion on Delay Modulation is included in Appendix B. The problem is compounded by the fact that the read out is in reverse, the recorder is not rewound prior to playback.

Normally a specific 5-bit pattern is required to resolve the phase ambiguity, but the manufacturer of the ESTR has made internal alterations to the units enabling a 3-bit pattern (010) to accomplish the same results. This represents a major accomplishment, since a specific 3-bit pattern has a much higher probability of occurring naturally in the data than a specific 5-bit pattern.

Recorded data input interrupts, as well as dropouts caused by tape defects, will cause a phase ambiguity condition which will degrade the BER performance. The 3-bit pattern (010) is required to rephase the data. Each input data stream to the recorder must be preceded and followed by this 3-bit pattern. The manufacturer of the ESTR recommends 3 to 5 inches of tape between both the data and the post preamble be stuffed with this 3-bit pattern to assure the correct phase for the data. They also recommend the 3-bit pattern occur periodically within the data to assure the proper phase in the event of a tape defect.

Differential Encoder -- The SSA system utilizes a suppressed carrier modulation/coherent carrier recovery technique, which results in a phase ambiguity problem similar to the one previously discussed. The squaring operation in a coherent carrier recovery loop acting on a suppressed carrier results in either of two stable phase states. The results being a possible logical inversion of the output data stream. This inversion will cause extremely long error bursts, which will be beyond the error correcting capability of the rate 1/3 Convolutional encoder and interleaver. The differential encoder is utilized by the DMU to solve the ambiguity. Figure 2.3 is a schematic of a typical differential encoder. The price paid for utilizing a differential encoder is that decoder output errors occur in pairs, i.e. a single error into the differential decoder results in two errors out.

Convolutional Encoding -- Convolutional encoding is required on all MA return links to minimize the EIRP requirements of user Spacecraft and thereby, to minimize the interference an MA user will create when it appears within the main beam supporting another MA user. Because all MA return links are modulated with a PN sequence, each MA user has a processing gain advantage over other MA users appearing within its beamwidth. This gain is defined by the ratio of PN chip rate to the desired user symbol rate. Despite the use of convolutional encoding and PN modulation, there is a finite probability that the interference caused by other MA users will degrade the return link service performance listed in Table 3.6 (i.e exceed the 1 dB MA self-interference degradation included in the TDRSS design). If the system users employ higher margins than the model used or if

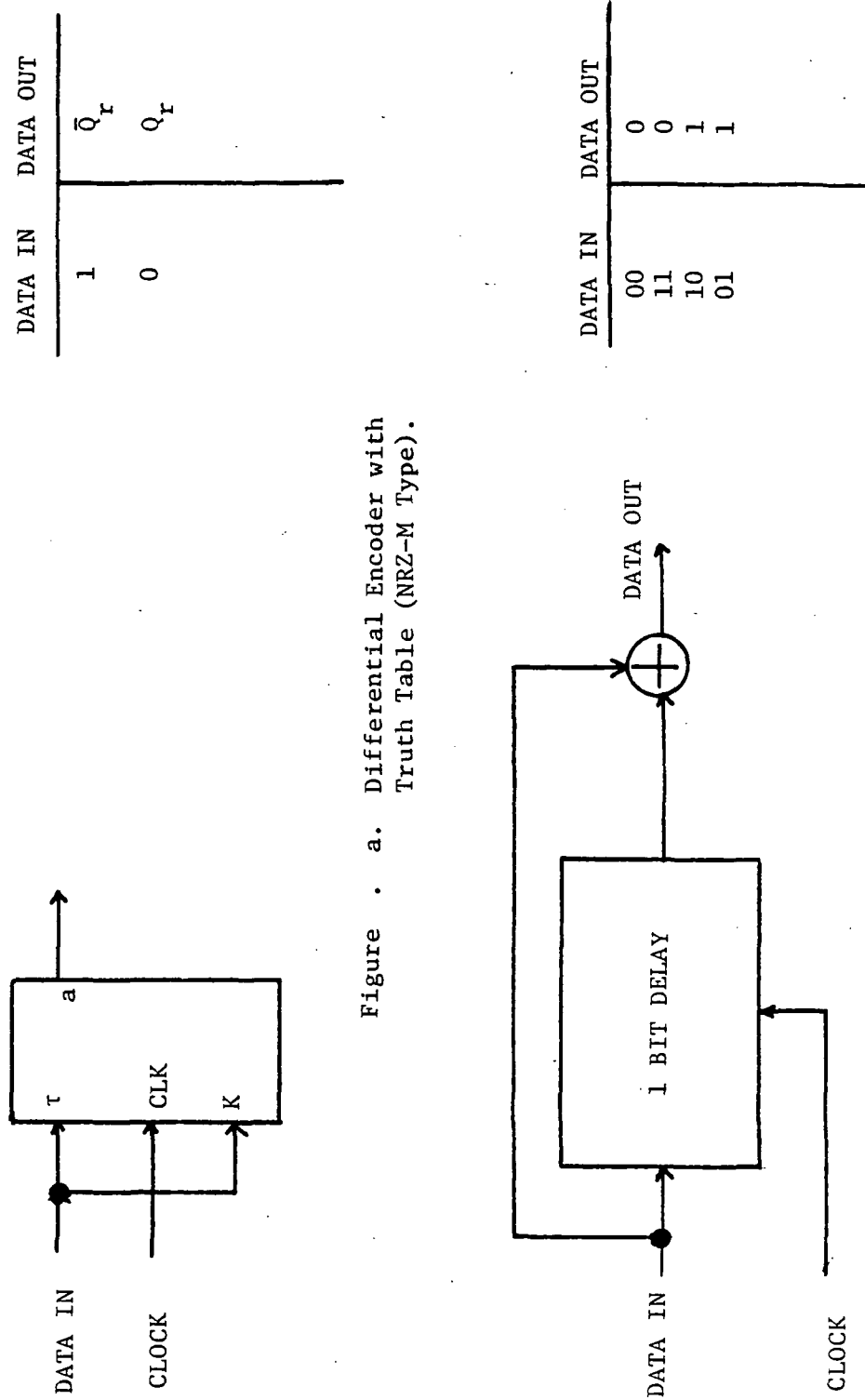


Figure . a. Differential Encoder with Truth Table (NRZ-M Type).

Figure 2.3. Differential Decoder with Truth Table.

a larger percentage of the users operate at higher data rates, the actual self-interference may exceed the 1-dB margin, resulting in degraded performance to low data rate users of the system.

As part of the network/user interface activities, the MA system user will be advised of potential degradations due to self interference (if any) and the potential interference to other users of the system due to a user's desired operation (e.g., large signal margin) will be considered. This coordination will insure that excessive EIRP margins are not used, thereby minimizing the system's self-interference.

The 1/2 rate convolutional encoder, and the ST unique PN-Code are required to meet the constraints placed on the ST by the TDRSS. They are utilized for CCIR flux density limitations. The TDRSS channel BER is boosted to 1×10^{-5} by the 1/2 rate convolutional encoder that outputs 2 symbols for a symbol in, and has constraint length 7. The Generator functions are:

1. $G_1 = 1111001$
2. $G_2 = 1011011$.

The symbols generated from G_2 can be either true or complemented. Figure 2.4 shows a block diagram of the rate 1/2 encoder. The diagram also shows that every other output symbol is inverted; this will aid the ground system with bit synchronization.

Rate 1/3 Convolutional Encoder -- The 1/3 rate convolutional encoder, the channel interleaver, and 30 PN encoder are required to meet the constraints placed on the ST by the TDRSS. They are utilized to combat the RFI problem, returning the TDRSS channel BER

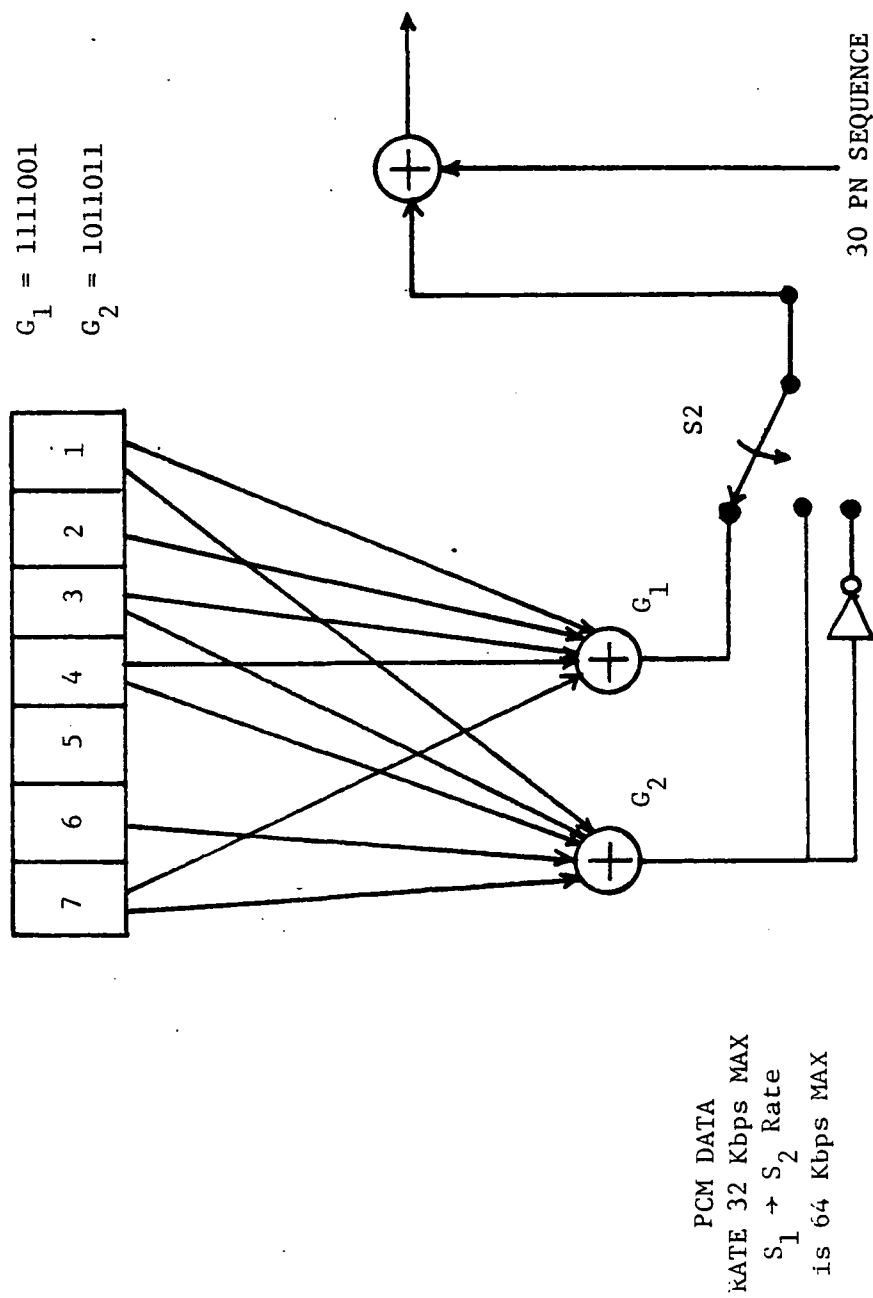


Figure 2.4. Convolutional Encoder With Cover Sequence.

to 1×10^{-5} . The 1/3 rate Convolutional encoder outputs 3 symbols for 1 symbol in and has constraint length 7. Figure 2.5 shows a block diagram of the encoder. The diagram also shows that every other output symbol is inverted. This will aid the ground system with bit synchronization.

Periodic Convolutional Interleaver -- The DMS utilizes a (30, 116) Periodic Convolutional Interleaver (PCI) with a cover sequence for synchronization in conjunction with the 1/3 convolutional encoder to counteract the burst errors caused by the RFI. The two units together will randomize a channel burst up to 30 symbols by separating any two adjacent input symbols by at least 120 symbols at the output.

The 30 PN sequence is modulo-2 added to the coded symbols prior to interleaving to provide a prior information for deinterleaving synchronization. Also, the deinterleaving sync, and Viterbi decoding branch sync, will occur simultaneously due to the prior relationship between the G_1 encoder symbol, the cover sequence and the interleaving zero delay element.

The 30 PN cover sequence is a truncated 31 maximal length sequence generated by $1 + X^3 + X^5$. The truncation is accomplished by the deletion of the shift register word 11110 (MSB) from the normal sequence. The output of the PN generator is interleaved prior to being modulo-2 added to the encoded bits.

The PCI is illustrated in Figure 2.6 as commutated delay elements. The input and output commutators are slaved, advanced for each encoded bit, and recycled every 30 symbols. The input to the

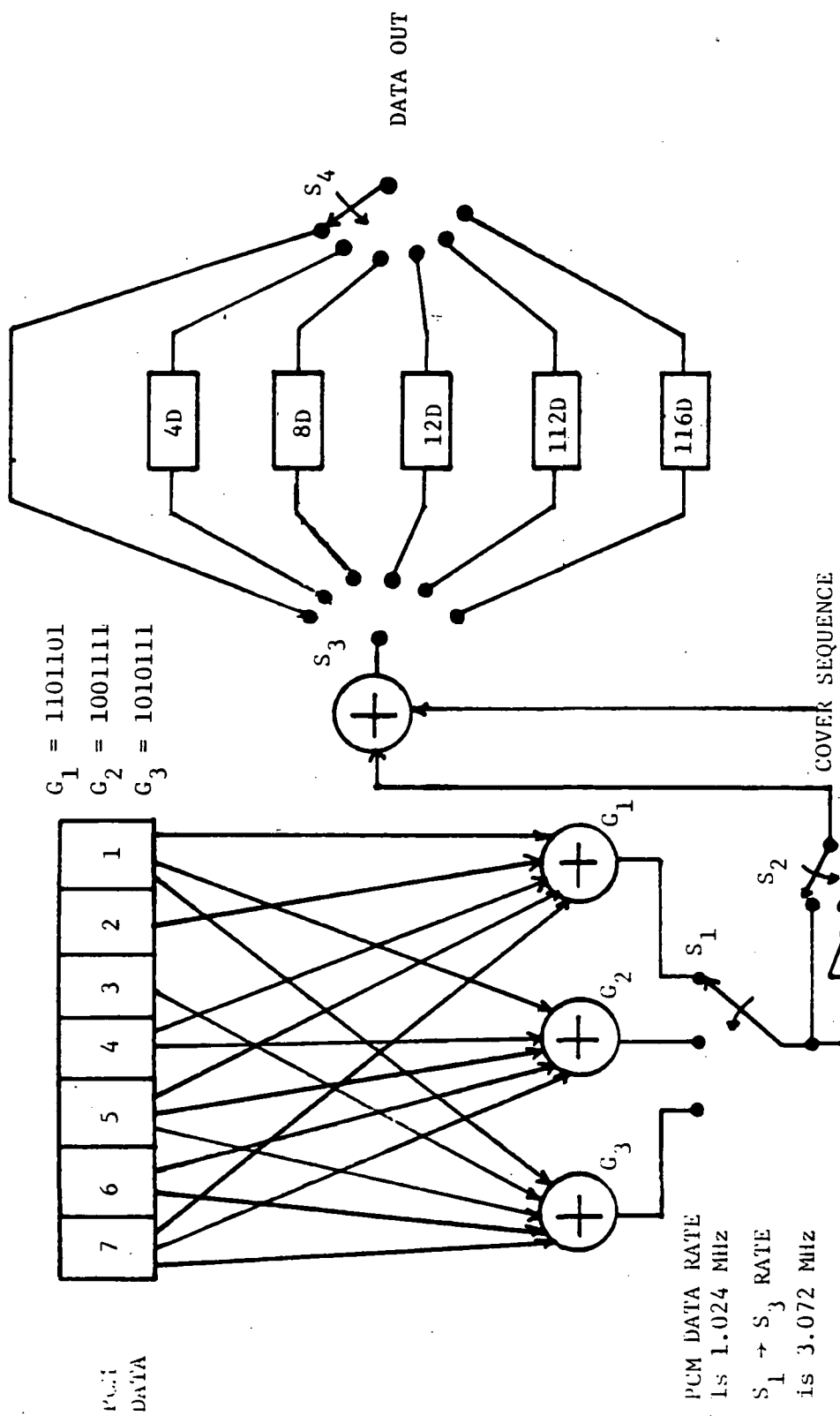


Figure 2.5. Convolutional Encoder with PCI and Cover Sequence.

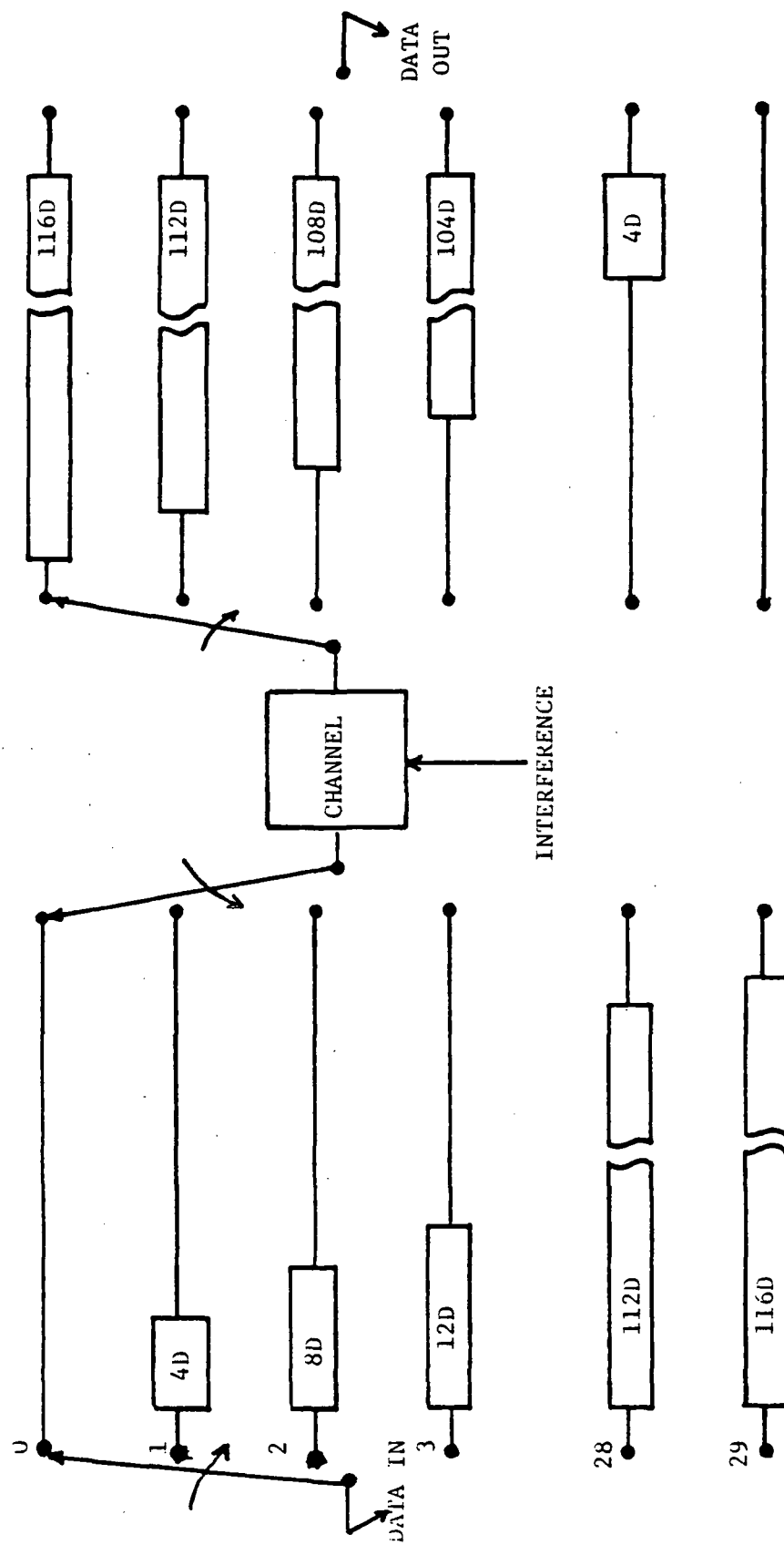


Figure 2.6. Periodic Convolutional Interleaver and Deinterleaver.

zero delay will always be a G_1 encoder symbol modulo-2 added to the initial cover sequence state.

2.A.4.b Instrumentation and Communication System. I(SSA Link)

The interleaved encoded data stream is routed to the I&C where it is used to biphase modulate (BPSK) a 2255.5 MHz 14 watt RF carrier.

The output of the SSA transmitter is multiplexed and switched to provide an RF path for transmission on the HGAs. The HGA system has a beam width of approximately 8.6 degrees providing a half power beam width gain of 22 DB permitting the SSA system to close the link to the TDRSS. The antenna has a two axis rotational control system permitting a close mechanical positioning of the antenna. There are two HGA's, one on either side of the ST that can be positioned so that extended transmission times are provided. A requirement to maintain a minimum 20 minutes contact time using one TDRS and one HGA can be achieved. The fine pointing and control subsystem utilizes a continuous instead of a discrete signal to control the positioning of the HGA, enabling the system to maintain the center of beam between the ST and TDRS during modulation. The HGA is a 1 meter dish with a 2° minimum full cone angle and has a gain of 24.5 dB at 1.0° off boresight.

2.A.4.c Instrumentation and Communications System. II (MA Link)

The encoded data stream is routed to the I&C where it is used to SQPN modulate a 2287.5 MHz, 5 watts RF carrier. The output of the MA transmitter is multiplexed and switched to provide a RF path for transmission. Engineering data at 4.0, 8.0, or 32.0 Kbps

and science data at 4.0 Kbps are transmitted to the TDRSS utilizing the transmitter portion of the MA transponder via the HGA system. Engineering data at .5 Kbps are transmitted via either the LGA or HGA systems. The MA transmitter utilized two simultaneous, independent channels employing spread spectrum.

The HGA system has a beam-width of approximately 8.6 degrees providing a half power beam width gain of 22 dB permitting the MA system to close the link to the TDRSS. The antenna has a two axis rotation. There are two HGA's, one on either side of the ST, that can be positioned so that extended transmission times are provided. One requirement is to maintain a minimum of 25 minutes constraint time used on TDRS and one HGA.

2.B Tracking and Data Relay Satellite System

The second main group, the return link from the ST to the ground station at White Sands, New Mexico, via the TDRSS is specified to have a BER of 1×10^{-5} if certain signal constraints are met. These constraints are listed in Reference 5.

2.B.1 Return Channel Link Model

The MA utilizes two simultaneous independent channel channels employing spread spectrum techniques for the transmission of real-time 4.0 Kbps science and .5, 1.0, 4.0, 8.0, or 32.0 Kbps engineering data. Engineering data may be transmitted on either the In-phase (I) or the Quadrature-phase (Q) channel at one of the above data rates or on both channels simultaneously at the same data rate.

Science data are transmitted on the (I) channel only. The MA system also provides a channel for direct communications with the Ground Space-Flight Tracking and Data Network (GSTDN).

The TDRSS channel is modeled as a memoryless additive White Gaussian Channel even though the channel is subject to both random and burst errors. The burst errors are due to the Radio Frequency Interference (RFI) encountered in certain areas of the world and also due to the inherent characteristics of the Viterbi decoder and the differential encoder.

Due to the lack of information (classified information) of the actual effect of the RFI in the return link channel, certain assumptions have been made. The RFI is assumed to degrade the link SNR by 1 dB at all times. It is assumed to cause a 2 dB loss for approximately 2 to 3 minutes per 90 minutes while the ST is in a region external to a 1.5° contour of this RFI area, and a 5 dB loss when the ST is within the 1.5° contour region. These reductions in SNR have been compensated for by a 2.5 dB increase in the EIRP and also restraining from transmission during high RFI periods.

2.B.2 Ground Station

At the ground station at White Sands, NM, the signal will be synchronized, deinterleaved, the PN sequence removed, convolutionally decoded using the Viterbi Algorithm and differentially decoded by the ground station at White Sands, NM.

The bit synchronizer was originally assumed to have a bit slip rate (BSR) of 1×10^{-11} . A bit slip refers to the addition or

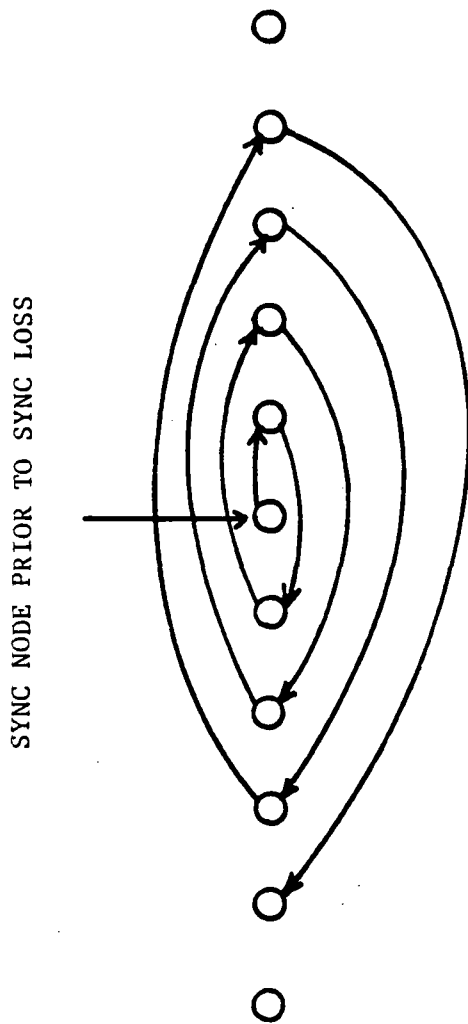
deleting of a bit to the incoming symbol sequence. However, the results of recent tests conducted by the manufacturers indicate a much lower BSR performance. The evaluation was conducted using various data rates from 100 Kbps to 3 Mbps with a $1/2$ rate convolutional coding. The channel was characterized by extreme adverse conditions and low signal-to-noise ratios. The ST will not transmit under the simulated conditions. During the several weeks in which the evaluation was conducted, not one occurrence of a carrier or a bit slip was detected.

The deinterleaver is said to be synchronized when the deinterleaving commutators are correctly synched to the interleaving commutators. The propagation delay of channel requires the symbols which are delayed through the $4x$ delay element ($x = 0, 1, 2, \dots, 29$) of the interleaver to be delayed through the $116 - 4x$ delay element of the deinterleaver. Thirty sync ambiguities exist in the deinterleaver as a result of the thirty positions of the deinterleaver commutator. An initial commutator position or sync state is selected and the results from the Viterbi decoder metric calculations are used to determine if the selected state is the correct sync word. If the results from the Viterbi decoder indicate an excessive number of errors, it is assumed that an incorrect sync state was selected and a different delay element is selected by the commutator. The decoder again performs the metric calculations and the results tested. Once the correct sync state is selected, the deinterleaver commutator will continue to advance for each input symbol and recycle every 30 symbols.

Since the deinterleaver utilized feedback from the decoder, it is possible to acquire false sync by locking on one of the sync nodes adjacent to the correct sync node. The partially deinterleaved sequence has a symbol error rate that is capable of being corrected by the decoder if the input error rate is low (little or no RFI).

The 30 PN cover sequence is employed to remedy this situation. The modulo-2 addition of the cover sequence to the encoded symbol prior to interleaving, and again to the deinterleaved symbols prior to decoding, will provide a symbol sequence to the decoder with a very high error rate for any sync node other than the correct sync node. This is due to the autocorrelation properties of the truncated maximal length sequence utilized to generate the cover sequence. Modulo-2, adding the PN cover sequence in this manner, assumes that the deinterleaver and decoder have essentially a zero probability of locking to any sync node other than the correct node.

The sync strategy for the deinterleaver requires that a search to acquire sync begin with the last sync node then shift alternately to the next adjacent nodes on the right and left. The sync strategy is shown in Figure 2.7. This strategy is beneficial when a system anomaly occurs, since only a minimal loss of data will occur. The quality indicator from the decoder metric calculations will determine with a very high probability that resynchronization is required. Thus, essentially no false resynchronization will occur and the failure to recognize the need for resynchronization will essentially be zero. This system also has the added advantage that the deinterleaver and decoder will be synchronized



- . Total of 30 sync nodes for (30,116) PCI
- . Sync search is always performed optionally as shown from first sync node.

Figure 2.7. Synchronization Strategy for the Periodic Convolutional Deinterleaver.

simultaneously, since the zero delay element of the interleaver commutators is synchronized to the G_1 symbols of the convolutional encoder. Since the decoder branch sync ambiguity is resolved simultaneously with the resolution of the correct deinterleaver sync node, this minimizes the time required to achieve initial synchronization and resynchronization.

The average number of states searched to acquire initial synchronization for the integrated interleaver/decoder is assumed to be 15. A time of 250 data bits is assumed to be the average sync time of the Viterbi decoder, since the decoder does not have to resolve the branch sync ambiguity. The average resynchronization time to recover from a single bit slip is expected to be less than 500 data bits.

The decoder utilizes the Viterbi algorithm and is a maximum likelihood decoder. A maximum likelihood decoder is one which compares the conditional probabilities, $P(y/x^{(m)})$, where y is the overall received sequence and $x^{(m)}$ is one of the possible transmitted sequences, and decides in favor of the maximum. One of the disadvantages of this type of decoder is that even at low error rates, decoding errors usually occur in bursts.

The output sequence of the Viterbi decoder is converted back to NRZ-L by the differential decoder prior to being released to the NASCOM terminal at White Sands.

2.C NASA Communications Network

The last main link in the overall system is the link from the NASCOM terminal at White Sands, NM, to the NASCOM terminal at GSFC,

via the DOMSAT system. As previously stated, the link has a BER of 1×10^{-7} averaged over a 24 hour period. The data is formulated into the standard 4800-bit NASCOM blocks and a polynomial error detecting code is utilized. This code will only detect errors and has no error correcting capabilities. This link is considered to be transparent and will not be included in the analysis.

Once the data sequence is received at GSFC, it is checked for transmission errors and routed to the STOC at GSFC. If an error is detected, it is tagged and transferred with the data.

2.D Assumptions

The next section is an analysis of the overall BER for the MA. The following assumptions were made.

1. The DOMSAT Link is transparent.
2. The ST MA link meets all the constraints required by the TDRSS to provide a BER of 5×10^{-3} , ie:
 - a. Rate 1/2 Convolutional Encoding.
 - b. Encoder constraint length of 7.
 - c. Soft decision (Q = 2 bit Quantization).
 - d. No degradation due to RFI.
 - e. 5×10^{-3} BER for (E_b/N_o) , of 4.05 dB.
 - f. Perfect synchronization is maintained.

CHAPTER 3

ANALYSIS OF THE PERFORMANCE OF THE MA RETURN LINK

This section is on analysis to determine the overall anticipated BER of the engineering data transmitted via the MA system and the scientific data transmitted via the MA system at a 4 Kbps rate. The coding scheme is the 1/2 Rate convolutional code with a Viterbi decoder and with the 30 bit PN code as shown in Figure 3.1.

3.A Probability of Error on the Inner Channel

This section will deal with determining the BER of inner channel. There are several aspects that must be considered in determining the inner channel BER and these are:

1. Bit transition density,
2. Tape recorders,
3. Synchronization,
4. Multiple Frame Format,
5. RFI, and
6. MA Self Interference.

3.A.1 Transition Density

The ability of the inner channel to meet the TDRSS requirements of at least 1 transition in every 64 symbols and at least 64 transitions in every 512 symbols is examined in this section. The configuration of the system is illustrated in Figure 3.1. The 1/2 Rate Convolutional encoder with alternate bit inversion of Figure 2.5 will be examined first.

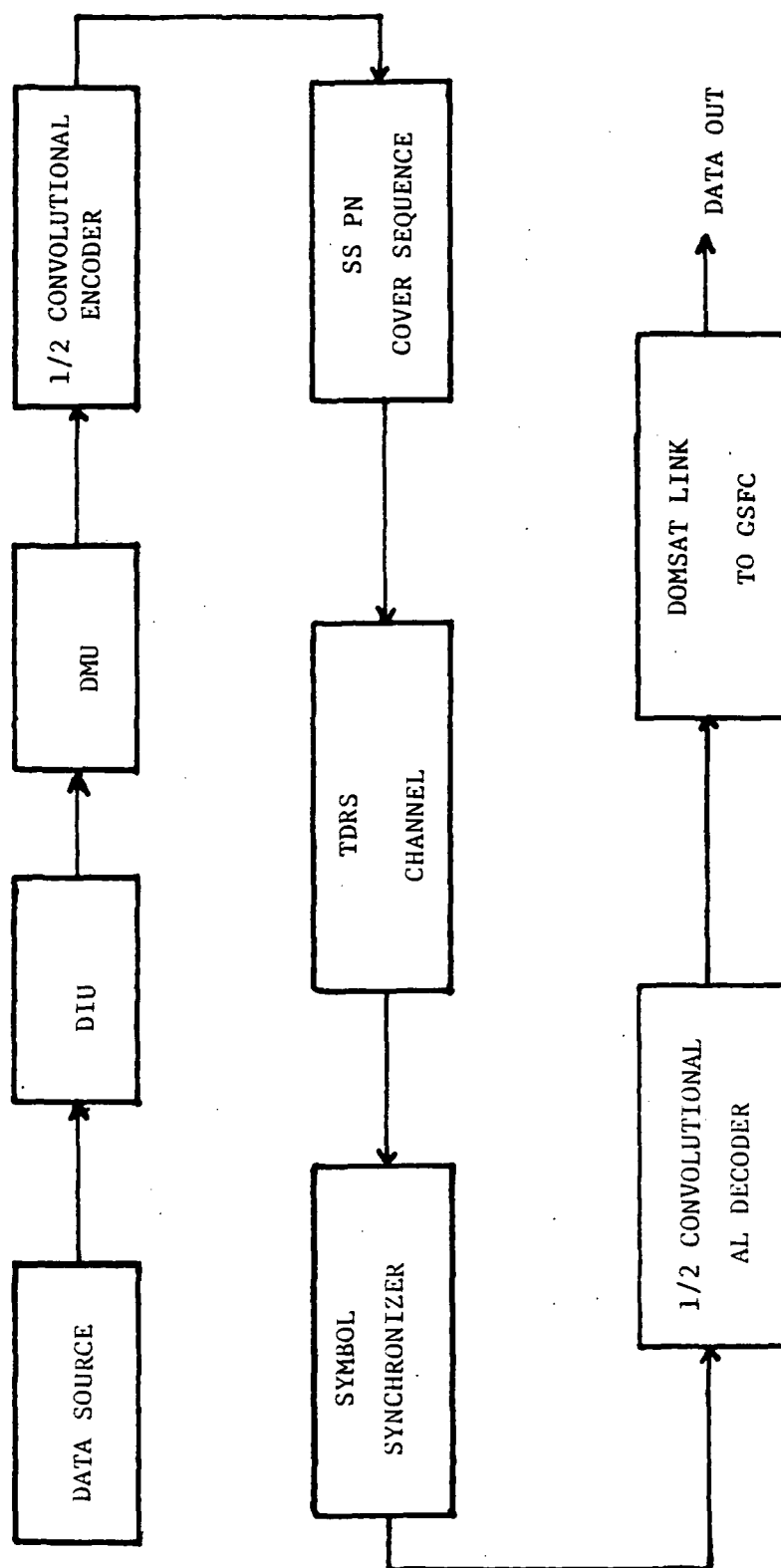


Figure 3.1. General ST/TDRSS Concatenated Coding Concept.

The following discussion concerning the output symbol transition density function of the 1/2 convolutional encoder with alternate symbol inversion is based on the material by M. K. Simon and T. F. Smith in Ref. 11. Simon and Smith have determined for a particular class of convolutional codes that alternate symbol inversion assures a maximum transition-free run of output symbols, and hence its maximum transition density. This maximum length is independent of the code generation or connections, and is dependent only on the code data source model and on the code constraint length and rate. Simon and Smith separate all 1/v Convolutional codes into three classes of codes: v even, v odd for transparent codes, and V odd for nontransparent codes. A transparent code is one which provides the complement of the output sequence for the complement of the input sequence.

A simple test to determine if a code is transparent is to determine if each row of the generator matrix C has an odd number of ones. If so, then the code is transparent. The generator matrix C for the 1/2 Convolutional Code employed by the ST is

$$C = \begin{bmatrix} 1111001 \\ 1011011 \end{bmatrix} \quad (3.1)$$

where the right hand column represents the present input and the left hand column represents the oldest (content of the last shift register K, the Code Constraint length) input.

Since $v = 2$ is even, and each row of C contains an odd number of ones, the convolutional code is a number of Case 1.

Simons and Smith state that for even v and transparent codes, the only input bit sequence that will produce an output alternating sequence longer than N_{\max} symbols is the alternating sequence itself. N_{\max} is defined as

$$N_{\max} = \mu + v = (n_1 + 1)v = ([\frac{K-1}{v-1}] + 1)v \quad (3.2)$$

Where K = the Code Constraint length; $[x]$ denote the smallest integer greater than or equal to x .

Furthermore, if the encoder is such that the alternating input sequence produces the alternating output sequence, then this output sequence can continue indefinitely, i.e., alternate symbol inversion will not produce a finite transition-free symbol sequence.

Reference 11 provides a test to determine if a Case 1 Code will produce an alternating output for an alternating input.

For rate $1/2$ codes ($v = 2$) we must have either both rows containing an even number of ones or both rows containing an odd number of ones in order to gain the above beneficial advantage of alternate symbol inversion.

Since a rate $1/2$ code with an even number of ones in both rows is catastrophic and a code with an odd number of ones in both rows is transparent, (i.e., the complement of the input sequence produces the complement of the output sequence), we conclude that the only non catastrophic rate $1/2$ codes which together with alternate symbol inversion yield a limited string of transition-free output symbols are those which are transparent.

Therefore, the maximum number of transition-free output symbols from the 1/2 convolutional encoder with alternate symbol inversion is:

$$N_{\max} = \left(\frac{K-1}{v-1} + 1 \right) v = \left(\frac{7-1}{2-1} + 1 \right) 2 = 7 \times 2 = 14 \quad . \quad (3.3)$$

Magnavox (Ref. 3) utilized an extensive computer analysis to arrive at an N_{\max} of 14 and BUAMERT, L.D. (Reference 10) used a slightly different mathematical approach to obtain an N_{\max} of 14. Thus, the maximum number of bits between transitions is 14 and therefore the system is guaranteed to meet the 1 in 64 requirement.

Simon and Smith also proved in Ref. 11 the 14 bit input sequence 10101001011001 yields the 16 symbol sequence 0010101010101011 which will occur in the encoder output sequence when alternate symbols are inverted and yields a decoded output of 1000000000000001. Neither this output sequence nor its complement can be repeated within the next 33 symbols. The next input will produce at least one additional bit transition, therefore the average bit transition for the worst case plus one additional input is 2 transitions per 16 output symbol which yields an average of 1 transition every 8 output symbols. If the 14-bit input sequence is 10101001011000, the output will be 10000000000000001100. If the 14-bit input sequence is 10101001011001, the output sequence will be 10000000000000001011.

Therefore, the rate 1/2 convolutional encoder with alternate bit inversion and generator matrix given in Equation 3.1 will meet both the 1 transition per 64 bit and 64 transitions in 512 or an average of 1 transition every 8-bits.

3.A.2 Tape Recorders

The ESTR's are subject to phase ambiguity as previously stated in Section 2. If it is assumed that the 3-bit pattern (010) required to re-phase the data appears with insufficient frequency within the data stream either naturally or as part of the fill and/or dummy data, then a BER for the recorders is established at less than 10^{-6} . The degradation to the overall BER due to this problem can thus be neglected similar to the BER of the DOMSAT link. Since the tape recorder has nearly a zero bit-slip rate according to the manufacturer, the main problem due to the tape recorder will be due to the bit reversal when the recorder is played back in the reverse order. It will be necessary to restore the correct order to the data prior to the Differential encoder/interleaver. A procedure to accomplish this was recommended in Reference 3 and it is assumed that this method or one similar will be utilized to resolve the problem.

Due to the above, the ESTR's are assumed to have essentially no effect on the overall error probability.

3.A.3 Synchronization

This section discusses the effect on the BER when one of the synchronization components of the system loses lock. Each element will be examined separately as an entity, where possible, and then

the interplay among the various components will be discussed. A total data loss due to synchronization loss will be estimated.

Loss of lock by the symbol synchronizer results in a trend toward an unlocking state for all system elements since all the data following sync loss is in error. Whether or not any given element unlocks depends upon the duration of the symbol synchronizer unlock and the flywheel effect of the elements that follow.

Due to the catastrophic nature of a symbol synchronizer loss of lock, it must be assumed that its probability of occurrence is extremely small under normal operating conditions. As previously stated, the symbol synchronizer has been tested and according to the manufacturer it has an extremely low probability of symbol synch loss, much less than the 10^{-11} assumed before testing.

For the low SNR of this system the acquisition time is expected to be on the order of 1000 symbols; thus, the data lost due to symbol synchronizer drop lock and reacquisition would be that which corresponds to the loss of 1000 symbols.

The loss of sync by any of the system elements will result in the loss of sync by the succeeding elements. If the symbol synchronizer loses lock for any length of time, the total system will require reacquisition of sync. This would involve the loss of

(6000 to 15000)

(3.4)

$= 6 \times 10^3$ to 15×10^3 bits of data.

TABLE 3.1

DATA LOSS ESTIMATES DUE TO SYNC LOSS

System Element	Data Loss Estimation (Information Bits)
Symbol Synchronizer	Dependent on elements following synchronizer and duration of drop lock
Viterbi Decoder/Channel Interleaver	6000 to 15000
TOTAL	6000 to 15000

3.A.4 Multiple Frame Format Operation

The multiple frame lengths of 1000, 2000, and 1024 can be present at the output of the engineering data frame synchronizer. The system operator will ensure that the frame synchronizers at the ground station are operationally reconfigured based upon a prior knowledge of the length being received.

3.A.5 Radio Frequency Interference

RFI may effect the transmitted signal in two ways. The RFI may cause an inverted bit stream output at the White Sands station as a result of a PSK demodulator carrier slip. The RFI energy may be sufficient to blanket the transmitted signal, make it appear as a sequence of consecutive bits of the same value; thus resulting in a possible loss of lock by the bit synchronizer at White Sands. The following paragraphs examine the probability that either of these conditions will occur. (Refer to Reference 15.)

First, the case of a PSK demodulator carrier slip at White Sands will be discussed. Since the signal is differentially encoded and interleaved, a demodulator carrier slip resulting in an inverted bit stream would be disastrous. A simple illustration is given in Appendix C. However, the PSK demodulator is a Costas loop which typically uses a slow response filter as the loop filter. Figure 3.2 is an illustration of a Costas loop. Once sync is achieved, the Costas loop will "ride out" small perturbations in the received waveform.

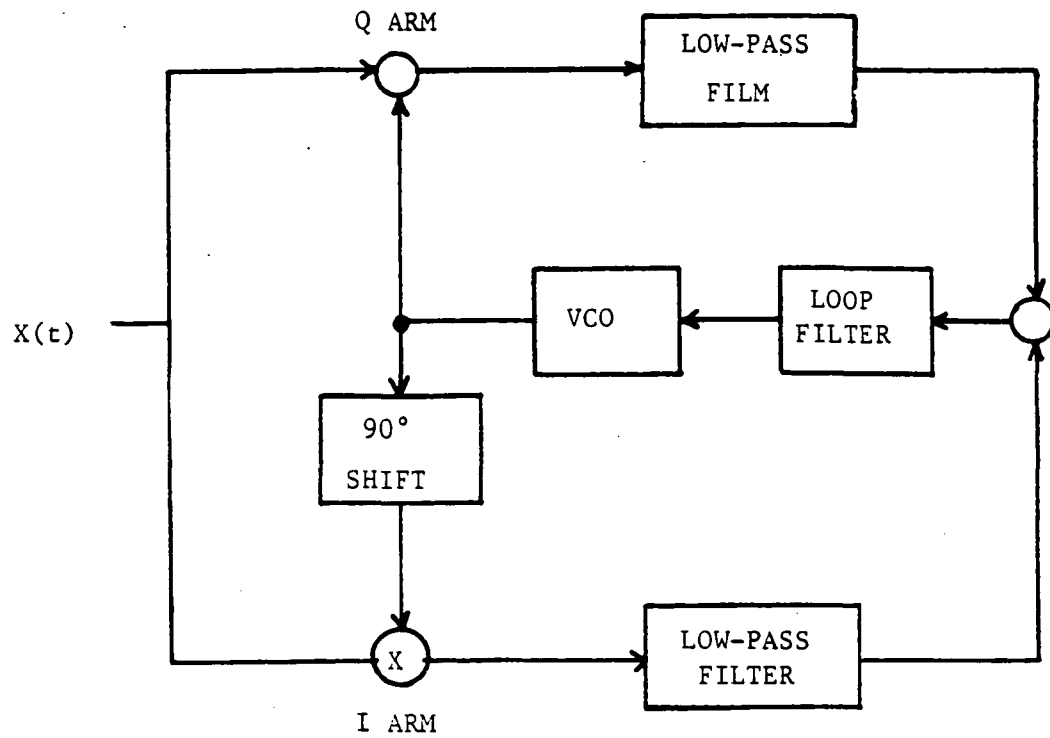


Figure 3.2. Costas Loop.

The PSK demodulator has a 100 Hz loop filter. Thus, the VCO control voltage variation is bounded by this response rate of 100 Hz. If the VCO carrier is allowed to vary a full 360° at 100 Hz rate, then in one millisecond only a 36° variation in the VCO could occur. A 36° variation would not create a carrier cycle slip if the PSK loop is initially in lock.

In order to create a 1 millisecond long period of erroneous phase in the signal, the RFI would have to exceed the link margin which is estimated to be 3.7 dBw minimum for a 1 millisecond period. A RFI signal of 3.7 dBw would be considered heavy RFI during which time the ST is not allowed to transmit as stated in Section 2.

For the sake of completeness, assume the ST does transmit during this time period and the RFI completely overrides the signal for a 1 millisecond period. The probability of this occurring may be estimated in the following manner.

The data describing the RFI for S band has been summarized as follows by GSFC:

Pulse Widths:	1 to 5 μ seconds
Repetition Rates:	1 K pulses/second
Aggregate pulse:	
Repetition Rates:	20 K pulses/second
Activity:	High.

The ST will be exposed to various levels of RFI during an orbit of approximately 90 minutes of which 20 minutes will be allotted for ST to TDRSS transmissions during a 76 minute lock time of availability.

If the RFI is assumed to be:

- . Approximately 1 minute is heavy RFI (≥ 5 dB)
- . Approximately 2-3 minutes is medium RFI (> 2 dB) ,

then the random reception of RFI pulses may be modeled by a Poisson Process.

Having made the above assumptions, the following discussion derives the probability of PSK carrier cycle slip. It will be shown to be extremely small and in fact is negligible.

Assume a certain event occurs randomly on the average of 2 times per second (averaged over a large interval T). Let K events occur in an interval of time τ . Then the probability of these K events occurring in a τ second interval is (for this case T = 2 minutes; the interval of heavy RFI and $\alpha = 20K$ RFI pulses per second received on the average and $\tau = 5 \mu\text{sec}$):

$$P_K(\tau) = \frac{(\alpha\tau)^K e^{-\alpha\tau}}{K!} = \frac{(\lambda\tau)^K e^{-\lambda\tau}}{K!}$$

$$= P_K(5\mu\text{sec}) = \frac{(.1)^K e^{-.1}}{K!} .$$

The parameter λ is called the poisson parameter and is equivalent to the average occurrence of the event in question

$$\lambda = 20 \times 10^3 = 2 \times 10^4 = \alpha .$$

We may tabulate the probability of λ pulses being received in a 5 μsec interval as

K	$P_K(5\mu\text{sec}) = [(.1)^K e^{-.1}] / K!$
0	0.90483741
1	0.090483741
2	0.004524187
3	.00015080625
.	.
.	.
.	.

Assume each pulse has constant width, w .

The case of interest is the probability of a series of pulses being received over a 1000 μsec period such that each pulse is received before the end of the preceeding pulse.

Let X = time between the arrival of the first pulse and the second pulse, then the probability is

$$\begin{aligned}
 P(X > 5\mu\text{sec}) &= e^{-(5 \times 10^{-6})(\alpha)} = e^{-(5 \times 10^{-6})(2 \times 10^4)} \\
 &= .90483741 \quad , \quad (3.6)
 \end{aligned}$$

which is the probability of zero pulses being received in 5 μsec .

The probability that a pulse will be received in 5 μsec or less is

$$1 - P(X > 5\mu\text{sec})$$

or

(3.7)

$$P(2^{\text{nd}} \text{ pulse occurs before } 5\mu\text{sec}) = .0951625819$$

For a 1 msec burst of RFI composed of 5μsec pulses each pulse is being emitted and received at random with an average emission and reception rate of 20K pulses per second. At least 200 pulses each within 5μsec of the previous pulse must be received independently of receiving 200 with proper timing. The probability of this occurring is bounded by

$$\begin{aligned} P(1 \text{ msec of continuous RFI}) &= P(\text{of } 5\mu\text{sec spacing})^{200} \\ &= (.904537418)^{200} = <<<< 0 \end{aligned} \quad (3.8)$$

Therefore, the chance of an RFI burst long enough to inhibit the TDRSS receiver of even 1μsec period is extremely remote, in fact a negligible probability.

The above case is seen to be the worst case, since the RFI pulses were assumed to have a constant maximum width. In the case of short width pulses, it would require many more received pulses to create a 1μsec burst. Hence, the probability of receiving a continuous pulse string is even more remote for variable pulse width. Therefore, the cases of PSK carrier slip due to RFI may be neglected.

The second problem caused by RFI is the case of possible channel symbol (bit sync) synchronizer loss. This case corresponds

to the situation of 65 μ sec of RFI of the same phase quadrant, resulting in a 65 μ sec string of like digits being transmitted from TDRSS to White Sands.

The SQPN Modulation used for MA Link eliminates this second problem.

3.A.6 SQPN Modulation

SQPN Modulation is used for DGI modes 1 and 2. With this feature, the spectral characteristics out of a saturated power amplifier will to a great degree, retain the spectral characteristics of the band limited input signal (refer to Appendix B), resulting in better control of out-of-band emissions. This provides more efficient communications and less interference to spacecraft using adjacent frequency channels.

3.A.7 Use of Identical Phase Shifted PN Codes on the I and Q Channels

For mode 1 operation, the I and Q Channels PN codes are generated from a single line of shift registers. The I and Q channels, PN codes are identical, but are offset by at least 20,000 chips. This separation is adequate for TDRSS to identify each data channel uniquely without requiring a unique linear shift register for each channel. User-unique PN Code assignments include shift register tap connections for generating the assigned codes.

3.B MA Self-Interference

The impact of self interference in the MA link is a direct function of the number of MA system users transmitting simultaneously

within the view of a given TDRSS. The EIRP of these users is in the direction of the TDRSS, and the MA antenna gain in the direction of such users.

The TDRSS MA System is a code division MA system with all users operating at the same frequency; this implies that all other users, when transmitting in view of a TDRS, will appear as additional noise to the signal of the desired user. The magnitude of this additional noise is directly proportional to the sum of the EIRP's weighted by the TDRS MA antenna gain in the direction of each user. As a result, the more users using the system and the higher their EIRP's (which may or may not be proportional to their data rate), the greater the MA self-interference.

The current TDRSS design provides a 1-dB margin against MA system self-interference which is based upon a conservative mission model assumption. If, however, the system users employ higher margins than the model used or if a larger percentage of the users operate at higher data rates, the actual self-interference may exceed the 1 dB margin resulting in degraded performance to low data rate users of the system.

An example of the variation in self-interference as a function of the number of high data rate users is shown in Figure 3.3.

The interference is given in terms of bit error rate degradation to a 1 Kb/sec user under the following assumptions:

1. All interfering users operate with a 3 dB margin.
2. The desired user margin is 0 dB.

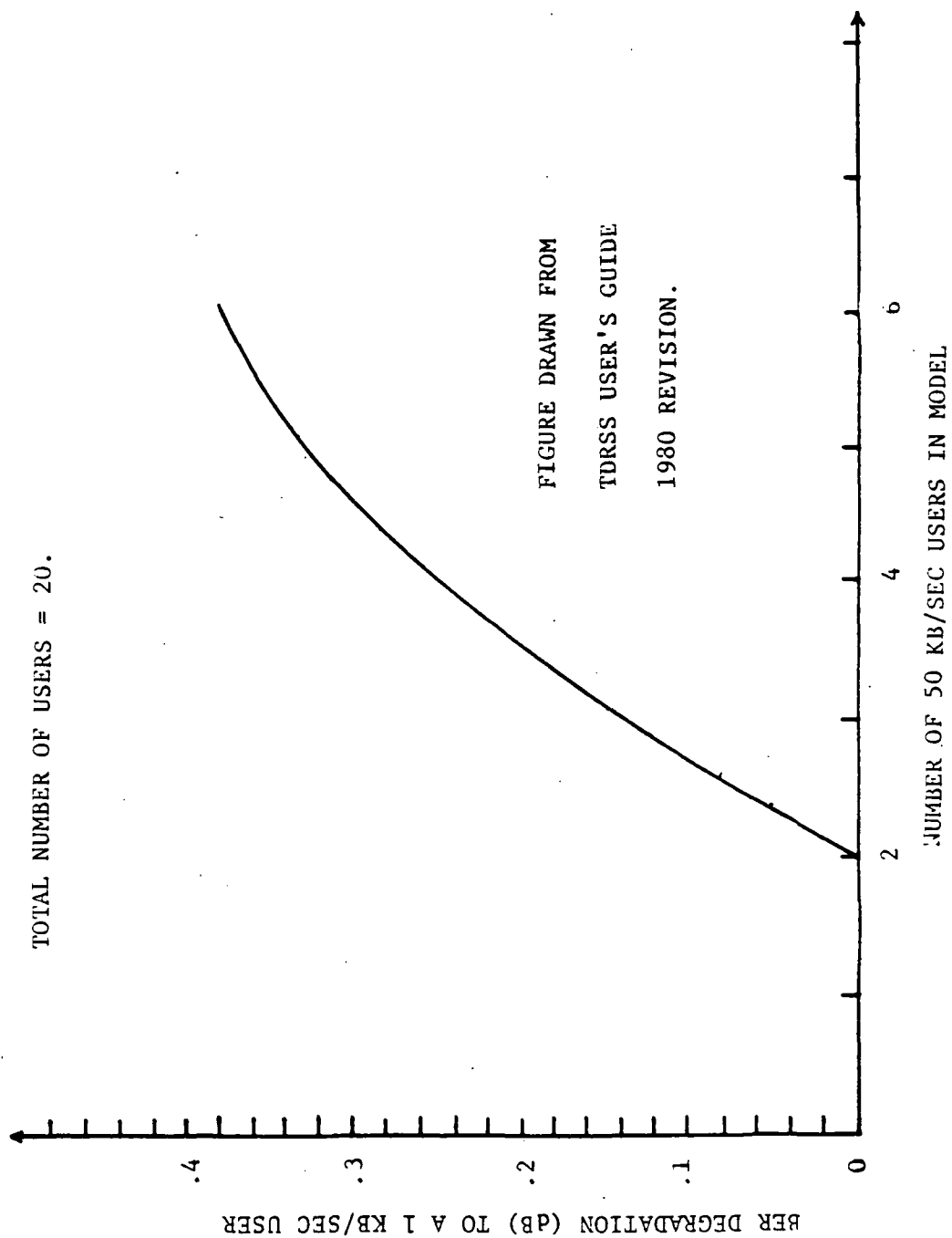


Figure 3.3. MA Self-Interference Degradation.

3. The other user data rates are selected to generate a 0 dB degradation with two 50 Kb/sec users (i.e. total self-interference = 1 dB).
4. Based upon statistical analysis, assuming all users except the desired user are in 2000 Km orbits with the desired user in a 300 Km orbit, the probability that the degradation will be less than or equal to the specified degradation is .99.

As part of the network/user interface activities, the MA system user will be advised of potential degradation due to self-interference (if any) and the potential interference to other users of the system due to a user's devised operation.

3.C Flux Density Effect on MA Return Link

Due to international requirements that the power density of an RF signal impinging on the earth be kept below a specified level, the MA users operating with low-gain antennas may not be able to utilize the maximum available coverage period without coordinating their transmissions with ground-based systems. For most potential users, this loss of coverage will not be significant (less than 5 percent of each orbit). However, for a user with an omni antenna in a low earth orbit and with a reasonable data rate, this loss could amount to 20 percent or more of each orbit.

The coverage loss curves shown in Appendix C illustrates the potential coverage loss in percent of an orbit as a function of user transmitter output power and telemetry bit rate. Because each bit rate curve represents a constant EIRP, as transmitter power increases antenna gain decreases.

As a result of the analysis, it is recommended that a user attempt to maximize his antenna gain and minimize the transmitter power output to minimize the coverage loss.

The expected bit error rate for the MA Link due to RFI and bit slip is shown in Table 3.2.

TABLE 3.2
EXPECTED BIT ERROR RATE FOR THE MA LINE DUE TO RFI AND BIT SLIP

OPERATING CONDITIONS	LINK MARGIN (dB)	EXPECTED SYSTEM BER	RECOMMENDATIONS
Case 1. Low RFI (~.7) dB No Bit Slip at White Sands.	3.7	$< 10^{-10}$	The System BER should meet the desired BER of 2.5×10^{-5} for this Case.
Case 2. Medium RFI 2 to 5 dB, no bit slip at White Sands.	3.7	$< 10^{-8}$	The System BER should meet the desired BER of 2.5×10^{-5} for this Case.
Case 3. Heavy RFI > 5 dB. No bit slip at White Sands.	1.2	$< 10^{-5}$	The System BER should meet the desired BER of 2.5×10^{-5} for this Case.
Case 4. Low RFI (~.7) 10^{-8} bit slip at White Sands.	3.7	4.2×10^{-5}	Further analysis is needed to determine the impact of BER and sync loss on the System.
Case 5. Medium RFI (2-5 dB) 10^{-11} bit slip rate at White Sands.	3.7	4.2×10^{-5}	Further analysis is needed to determine the impact of BER and sync loss on the System.

Assumptions: 1) The BER from ST to White sands is 1×10^{-5} .
2) The BER from White Sands to STOCC at GSFC is 1×10^{-7} .
3) ST signal meets all other TDRSS requirements of Reference 1.

NOTE: 1) The ST will not be allowed to transmit during periods of heavy RFI.
2) The BER for Case IV and V is based on the lowest estimates for total data loss
from Table 3.1.

CHAPTER 4

RECOMMENDATIONS AND RESULTS

The analysis in Section III indicates the MA return link should expect a BER of less than 10^{-7} . This estimate is somewhat misleading since the system susceptibility to synchronization loss was not accurately represented and this fact is clearly illustrated by Cases 4 and 5 in Table 3.2. If a bit slip rate as low as 10^{-11} is assumed, the bit slip rate becomes the main controlling factor for the overall BER. A bit slip rate of 10^{-11} means the total system would lose sync once every 10^{11} channel symbols resulting in the loss of 1.4×10^4 to 3.1×10^4 information bits since one information bit equals 3 channel symbols. There are 3.3×10^{10} information bits between slips, and the BER can be calculated using the following equation:

$$\text{BER} = \frac{\text{Number of Information Bits Lost Due to a Slip}}{\text{Number of Information Bits Between Slips}} \quad (4.1)$$

Substituting into Equation 4.1, the BER for the best Case (1.4×10^4 information bits lost) and worst Case (3.1×10^4 information bits lost) is found to be:

$$\text{Best Case} \quad \text{BER} = \frac{1.4 \times 10^4}{3.3 \times 10^{10}} = 4.2 \times 10^{-7} \quad ,$$

$$\text{Worst Case} \quad \text{BER} = \frac{3.1 \times 10^4}{3.3 \times 10^{10}} = 9.3 \times 10^{-7} \quad ,$$

which is a considerably higher BER than due to RFI.

A similar analysis would illustrate the effect on the system's BER due to the probability of sync loss by the other components. Thus, the probability of sync loss for those components must be determined and included in the analysis for the system's BER.

An evaluation of the 1/3 rate Viterbi decoder should also be conducted to determine its actual operating characteristics, since the output burst error property of the Viterbi decoder has a direct effect on the probability of the PN cover sequence losing sync.

The BER for the ESTR was stated to be 10^{-6} or better and its effect on the overall BER was neglected in Section 3. In actuality the ESTR may have substantial effect on the overall system BER due to the phase ambiguity resulting from converting to and from the recording code (delay modulation). For this reason, the bit structure of the dummy data should be such that the 3 bit sync pattern does appear frequently within the dummy segment.

The EIRP is another of the variables which has a substantial influence on the overall MA link BER. Table 4.1 lists the TDRSS EIRP requirements for the MA link. A reduction in the EIRP will result in an increase in the BER. For example if the antenna pointing system is off 4.6° from the center of the beam between the ST and TDRS, the EIRP will be reduced by approximately 2 dB. This will increase the BER by at least two orders of magnitude (Case 2 of Table 4.2), assuming the link margin is held constant.

TABLE 4.1
TDRSS EIRP REQUIREMENTS FOR THE
MA RETURN LINK

Assumed Information (uncoded) Data Rate = 5×10^4 bps

Coded (1/2 Rate) Data PF Channel Rate = 10^5 bps

Data Group 1, Modes 1 & 2

	January 1980
Uncoded required	27.59 dBw
Rate 1/2 Coded Required EIRP	22.39 dBw
Achievable Data Rate Without Coding dB (relative to 1b/sec)	19.4 + EIRP
Achievable Data Rate With Rate 1/2 Coding. (dB relative to 1b/sec)	24.6 + EIRP

NOTE: Coding Rate 1/2 Assumes (5.2) dB gain; hence, requiring less EIRP.

EXAMPLE BIT RATE = 5×10^4 bps $10 \log_{10} 5 \times 10^4 = 46.99 + \text{EIRP}$;

Thus, EIRP required = $46.99 - 19.4 = 27.59$ dbw.

TABLE 4.2

MA PREDICTED PERFORMANCE

MODIFIED SYSTEM EIRP = 27.5 dBw, Rate 1/2 Convolutional Encoder.

EIRP required by TDRSS for 10^{-5} BER using 1/2 Rate coding = 24.3 dB (25.0 dBw) (Ref. 5, page 2.22, paragraph 2.3.2.2.1 refers to rate 1/2 coding requirement) Line Margin = 4.4 dB (3.7 dBw) and Expected BER = 10^{-5} .

Case 1. Using Rate 1/3 convolutional encoding, we may expect 0.5 dB increase (Ref. 18) In effective SNR over rate 1/2 Convolutional encoding. Even though the WU TDRSS System will not guarantee an increase in performance over 10^{-5} BER an estimate is possible 10^{-5} BER out of Rate 1/2 VD is Equivalent to a 4.7 dB SNR into the Rate 1/2 decoder (Ref. 14). A Rate 1/3 encoded/decoded system should provide an average BER of 5×10^{-7} in theory. A performance curve for the linkabit iv 7015 ir decoder (Rate 1/3) shows an average BER of 10^{-6} (Ref. 2 and Figure 4.1).

Link Margin = 4.4 dBw (3.7 dBw) and expected BER = 10^{-6} at worst. Using concatenated RS/CE/VD we observe from Figure 4.2 the expected BER is much less than 10^{-12} , Ref. 2, page 1.3.

Case 2. Using Rate 1/2 Convolutional encoding and R/S concatenation we must consider the burst lengths possible from the VD decoder and the probability of such bursts. Using a set of curves comparing the performance of Viterbi Decoding Rate 1/2 (linkabit data) and Rate 1/3 (Bolson Data) (See Figure 3.3 and Ref. 2). One may degrade the channel by .2 dB (assumed to be due to RFI) which (holding the link margin constant) will yield an output BER of approximately 1×10^{-3} for Rate 1/3 (drawn of Figure 4.1). From Figure 3.3 we see that the average burst length would be approximately 12 bits long with approximately 6 bits being in error (these are (VD) output Bits).

TABLE 4.2 (Continued)

The average BER should still be less than 10^{-10} (from Figure 4.2 with BER from $VD = 5 \times 10^{-4}$).

Table 4.1 is a summary of the material used to calculate the values listed for Cases 1 and 2 in Table 4.2 and the conditions under which these values are valid.

For Case 3 the minimum value of $P_{VD}(E)$ which will still maintain the desired overall BER of 10^{-7} was determined using Figure 4.1. Figure 4.2 was employed to obtain the minimum (E_b/N_o) that would provide the required $P_{VD}(E)$. This value for (E_b/N_o) was subtracted from the minimum (E_b/N_o) (4.05 dB plus the 3.7 dB minimum expected link margin per reference 19) to yield the link margins listed in Table 3.2.

Taking into account the duplications and assumptions necessary to perform the analysis of sections 3, the MA return link should still exceed the desired bit error rate of no more than one error in 4×10^4 bits. This is due mainly to the margins built in the system, and to the results of tests conducted by the various manufacturers as stated in the preceding sections.

The system may even be able to operate during periods of heavy RFI.

It is recommended that during periods of heavy RFI the system be used so as to determine both the actual performance capabilities of the system and to determine the actual RFI structure. Both of these objectives could be achieved through transmission of known bit patterns with specific structure.

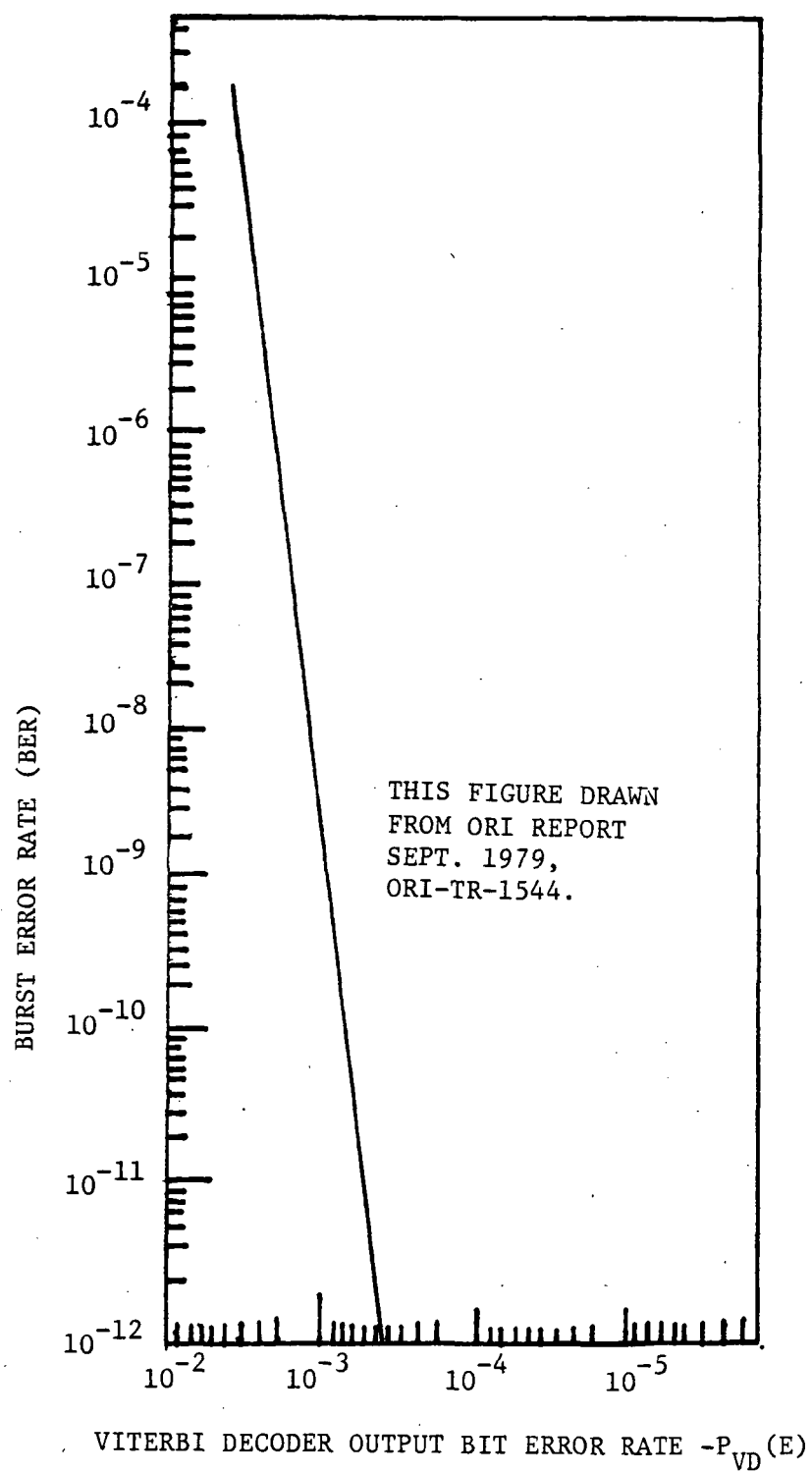


Figure 4-1. Concatenated Coding BER Versus TDRSS
Channel Viterbi Decoded BER for R/S ($\tau=8$).

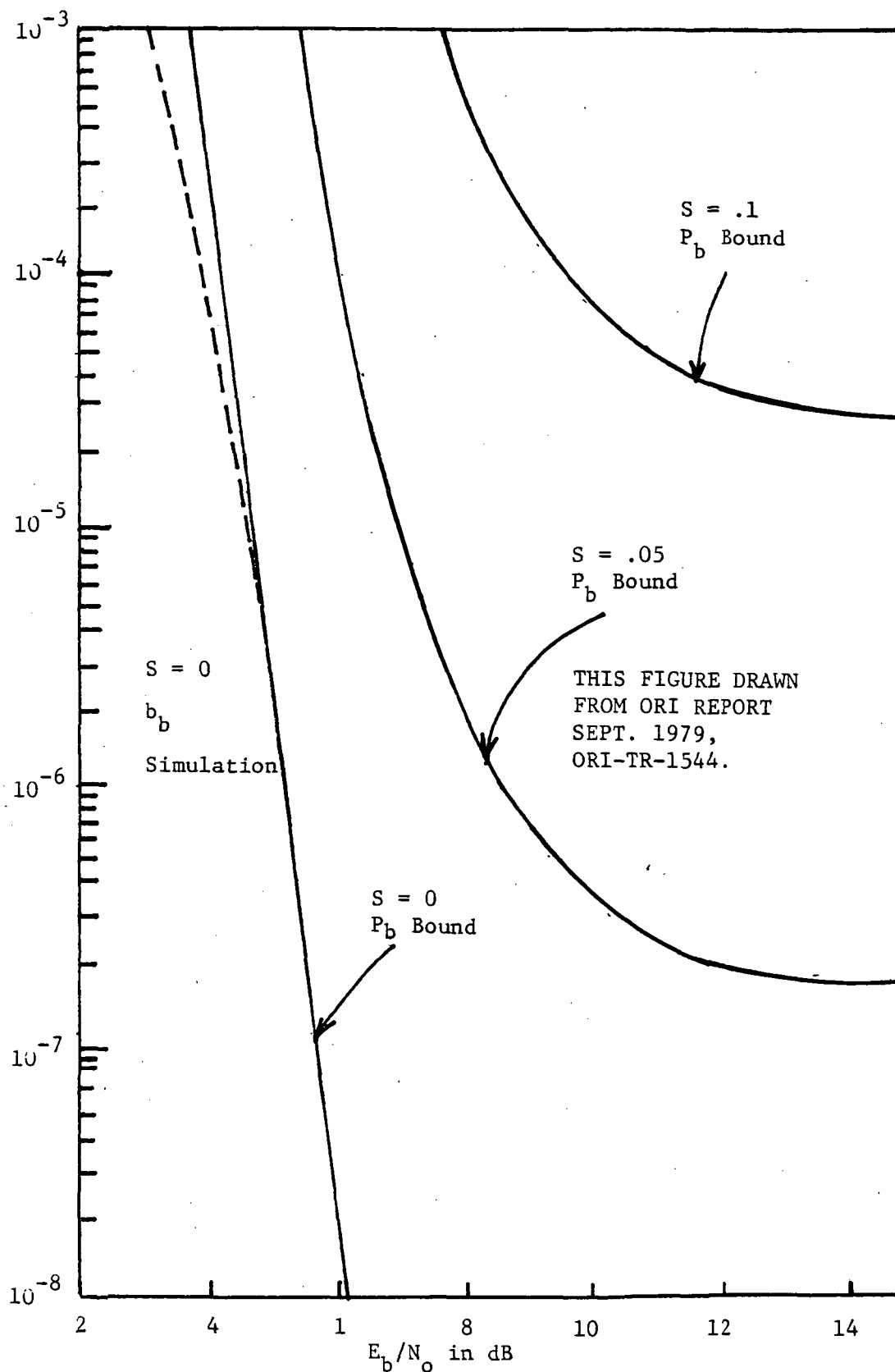


Figure 4.2. Error Rate Performance of K=7, R=1/2 System With Satellite RFI Blanking.

APPENDICES

APPENDIX A

EXAMPLE OF A REED/SOLOMON ENCODER/INTERLEAVER

APPENDIX A

EXAMPLE OF A REED/SOLOMON ENCODER/INTERLEAVER

One information packet of 14 segments with 1024 bits per segment is to be coded. This will require 224 rows of the 239 rows reserved for information. The remaining 15 rows are considered to be filled with zeroes. The packet is passed by the R/S coder unchanged. After the last bit of the packet is passed by R/S coder, the 16 rows of check bits are sent.

Each of the eight R/S codes consist of 255 symbols of 8 bits, 239 information symbols and 16 check symbols. Let each symbol be an element of the Matrix. Using matrix notation, the R/S codes can be written in terms of data symbols and check symbols by

$$\text{R/S code \#}M = A_{9-M}.$$

Example:

$$\text{R/S code \#1} = [A_{1,8}, A_{2,8}, A_{3,8}, \dots, A_{239,8}, A_{240,8}, A_{241,8}, \dots, A_{255,8}]^T$$

The R/S codes can also be written in terms of data bits and check bit by

$$R/S \text{ code } \#M = 1_{(8M+b)+64a} \begin{bmatrix} 0 \\ b=-7 \end{bmatrix}_{a=0}^{238}, P_{(8M+b)+64a} \begin{bmatrix} 15 \\ b=-7 \end{bmatrix}_{a=0}$$

Example:

$$R/S \text{ code } \#1 = [I_1, I_2, I_3, I_4, I_5, I_6, I_7, I_8; I_{65}, I_{66}, \dots, I_{15285};$$

$$P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8; P_{65}, P_{66}, \dots, P_{968}]^T.$$

Since the information is read into the R/S system by rows and read out by rows, the system appears to have an interleaver of length 8, but the data is passed undisturbed.

An input of the form

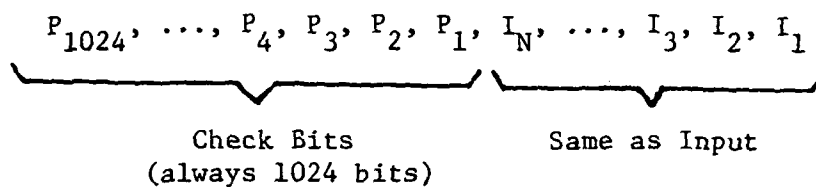
$$I_N, \dots, I_3, I_3, I_1$$

$$N \leq 15,295$$

will have an output of the form

$$\dots, S_{2,7}, S_{2,8}, S_{1,1}, S_{1,2}, S_{1,3}, S_{1,4}, S_{1,5}, S_{1,6}, S_{1,7}, S_{1,8}$$

where $S_{n,m}$ is the element in the n^{th} row and m^{th} column of the matrix which is, also, the n^{th} symbol of the R/S code number 9-M or in terms of bits



I_1 represents bit one of the information data.

P_1 represents check bit one

Input to R/S encoder

$$I_N \dots I_4 I_3 I_2 I_1 \qquad N \leq 15,296$$

Output of R/S encoder

$$P_{1024} \dots P_3 P_2 P_1 I_N \dots I_4 I_3 I_2 I_1$$

Same as Input

APPENDIX B

DELAY MODULATION (MILLER COMPLEMENT)

APPENDIX B

DELAY MODULATION (MILLER COMPLEMENT)

Delay Modulation (DM) is a procedure for encoding binary data into rectangular waveforms of two levels according to the following rules:

1. A zero is represented by a transition from one level to the other at the midpoint of the bit cell.
2. A one is represented by no transition unless it is followed by another one. The case of consecutive ones is represented by a transition at the end of the leading one bit cell.

These rules are illustrated in Figure B.1.

Delay Modulation has several attractive properties:

1. The majority of the signaling energy lies in frequencies less than one-half the symbol rate.
2. The power spectrum is small in the vicinity of $f = 0$ (that is at D.C.).
3. DM provides at most one transition per bit cell and at the least 2 bit transitions every 3 bit cells; thus, providing a bit stream with a very high bit transition density.

These properties provide DM with the advantage of inherent self-timing information using phase modulation which is not present in NRZ-L, while requiring approximately the same bandwidth as NRZ-L.

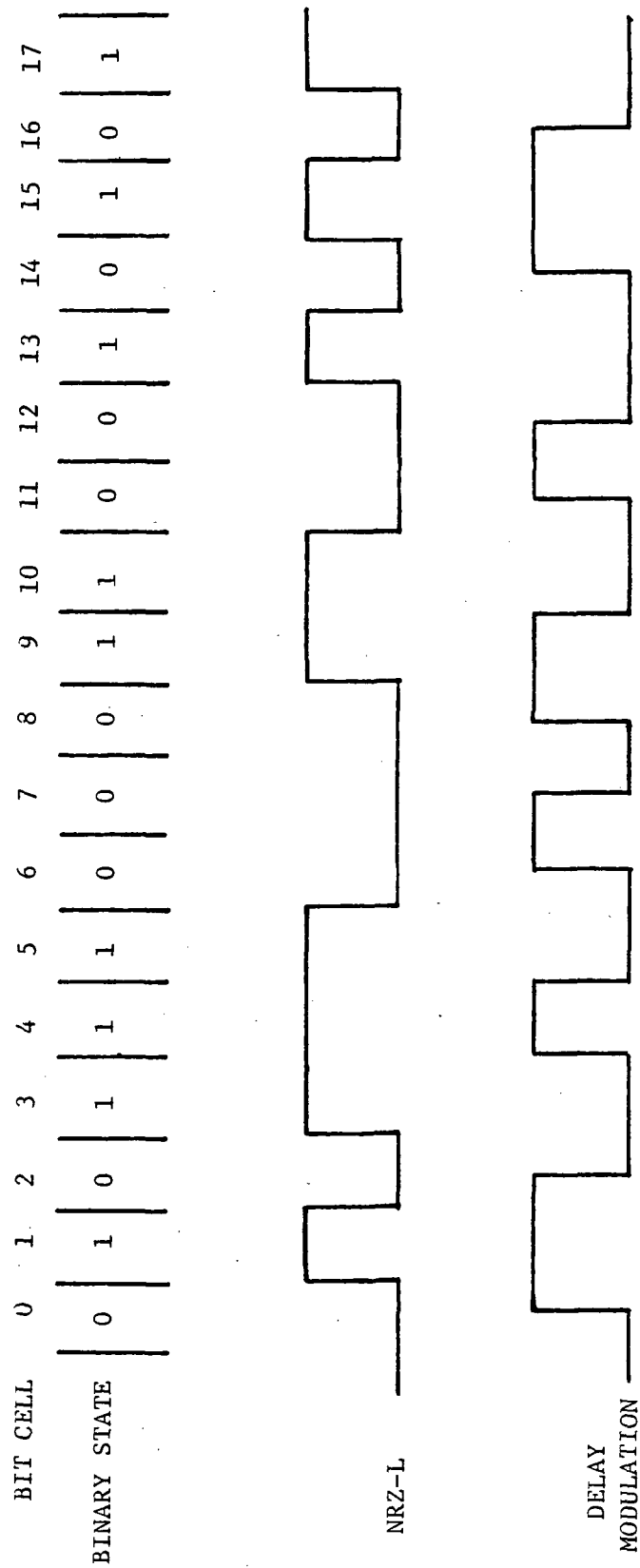


Figure B.1. NRA-L and Delay Modulation Binary Signal Waveforms.

DM is also suitable for use with tape recorders, especially when higher packing density is required, or with systems which require high bit transition densities.

DM requires a given 3 bit sequence to assure proper bit sync. This sequence is 010. This sequence has a high probability of occurring one or more times in any random data bit stream. The probability that one or more 010-bit sequences will occur increases rapidly as the number of bits in the data sequence increases. The following equation may be used to obtain a close approximation of the probability of 010 occurring n or more times in m bits (the number of bits per sequence).

$$P_m(010 \geq n) = 1 - P_m(010 \leq n) = 1 - [P_m(010 = 0) + P_m(010 = 1) + \dots + P_m(010 = (n - .1))]$$

Where:

$$P_m(010 = r) = \binom{k}{r} (q_0^{k-r}) (p_0^r)$$

$$q_0 = \text{the probability of any 3 bits not being 010} = \frac{7}{8}$$

$$p_0 = \text{the probability of any 3 bits being 010} = \frac{1}{8}$$

$$k = m - 2$$

$$\binom{k}{r} = \frac{k!}{(k - r)!r!}$$

For example, let m be 16 (for 16 binary bits) then the probability of a 010-bit sequence occurring one or more times is:

$$\begin{aligned}
 P_{16}(010 = 1) &= 1 - P(010 = 0) \\
 &= 1 - \binom{14}{0} \left(\frac{7}{8}\right)^{14} \left(\frac{1}{8}\right)^1 = 1 - \frac{14!}{14!0!} \left(\frac{7}{8}\right)^{14} = 1 - \left(\frac{7}{8}\right)^{14} = 1 - .154 = .846
 \end{aligned}$$

In other words, there is a 84.6% probability of a 010 pattern occurring and hence providing bit sync for a 16 bit sequence. Thus, we should expect a bit sync lock within a very short time upon the start of a DM encoded sequence.

APPENDIX C

EXAMPLE OF A CONCATENATED CODE

APPENDIX C

EXAMPLE OF A CONCATENATED CODE

Let us start with a code which is being used for error protection over a BSC channel. (Note this type of channel is a Digital error type or hard decision type channel).

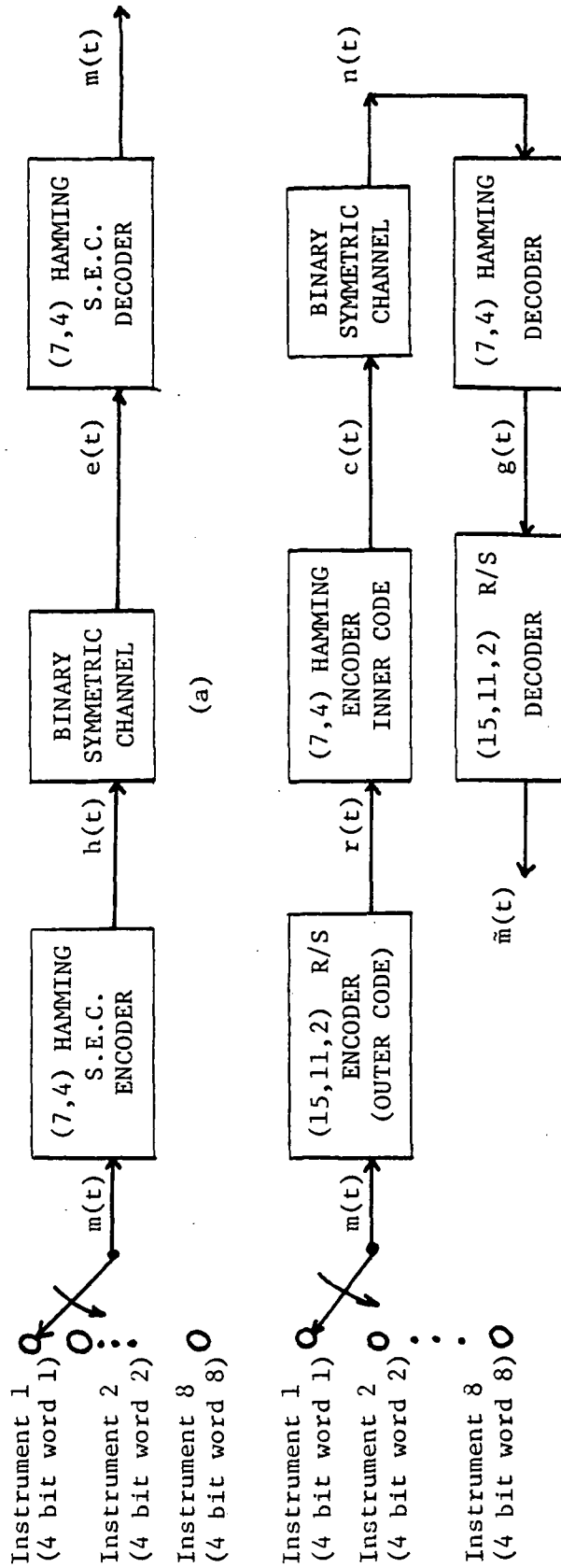
If we use a Hamming (7,4) SEC code (Figure C.1a) and if the probability of a bit being transmitted in error is $p = .025$, then the probability of a transmitted code word not being received (either with 0 errors or with a single correctable error) is

$$P(u \text{ not received correctly}) = 1 - [P(0 \text{ errors}) + P(1 \text{ error})]$$

$$= \sum_{k=2}^7 \binom{7}{k} p^k (1-p)^{7-k} = .012071453 = .0121 .$$

Now ask yourself how many different messages can we send with a Hamming (7,4) SEC code? The answer is of course 16 (or 15 if all zeroes are not used.)

Suppose we now construct a situation in which we have a source alphabet of 11 symbols. [If these were binary symbols, we could send 2^{11} messages = 2048. If these are 16 level symbols, we can send $16^{11} = 1.7592186 \times 10^{13}$ messages!]. Now, to send our original data, we merely encode 44 bit chunks rather than 4 bit chunks.



$$\begin{aligned}
 m(t) &= (WD8) \dots (WD2) (WD1) \\
 n(t) &= (C_1 C_2 C_3 WD8) \dots (C_1 C_2 C_3 WD2) (C_1 C_2 C_3 WD1) \\
 e(t) &= (C_1 C_2 C_3 WD8) \dots (C_1 C_2 C_3 WD2) (C_1 C_2 C_3 WD1) \\
 \tilde{m}(t) &= (WD8) \dots (WD2) (WD1) \\
 r(t) &= (P_1 P_2 P_3 P_4 WD22 WD21 \dots WD12) (P_1 P_2 P_3 P_4 WD11 \dots WD1) \\
 c(t) &= (C_1 C_2 C_3 P_1) (C_1 C_2 C_3 P_2) \dots (C_1 C_2 C_3 WD2) (C_1 C_2 C_3 WD1) \\
 n(t) &= (C_1 C_2 C_3 P_1) (C_1 C_2 C_3 P_2) \dots (C_1 C_2 C_3 WD2) (C_1 C_2 C_3 WD1) \\
 g(t) &= (P_1 P_2 P_3 P_4 WD22 \dots WD12) (P_1 P_2 P_3 P_4 WD11 \dots WD2 WD1) \\
 m(t) &= (WD21) \dots (WD2) (WD1)
 \end{aligned}$$

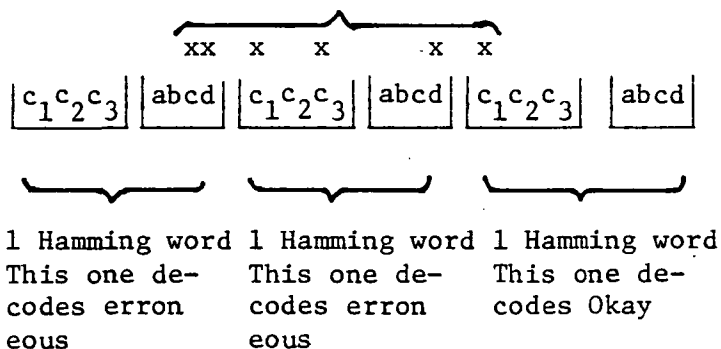
Figure C.3. Concatenated Codes.

We use a R/S code that has as many different symbols as the original code accepted for messages. That is if the original code (outer code) accepted 4 bit message streams then each R/S symbol must be expressable as 4 bits. Thus, if (7,4) code is outer code $2^4 = 16$ possible messages. Hence, R/S symbol must be 4 bits or 16 levels.

The probability of an error is now twofold in nature. Each channel transmission consists of one R/S symbol (4 bits) followed by 3 check digits for 7 total bits. Thus, it required an 11 digit burst to create a problem for the overall decoded output, since for a burst of 10 digit length only two R/S symbols are corrupted. (Remember the Hamming codewords can correct 1 error each.)

Channel Bit Stream =

Burst Length = 10



\dots $\boxed{\text{abcd}}$ $\overset{x}{\boxed{\text{abcd}}}$ $\overset{x}{\boxed{\text{abcd}}}$ $\boxed{\text{abcd}}$ $\boxed{\text{to R/X Decoder}}$ \rightarrow output correct.

can correct 2 of 15

Thus, a burst capability of 10 bits is now possible compared to the original 1 bit burst.

For random errors, we can correct up to 2 R/S symbols per 15 R/S symbols. Each symbol has probability of error equal to Prob. of word error of (7,4) SEC \cong .0121.

$$\begin{aligned} \therefore \text{Prob}(\text{of error}) &= 1 - [P_{\text{R/S}}^{(0 \text{ errors})} + P_{\text{R/S}}^{(1 \text{ errors})} + P_{\text{R/S}}^{(2 \text{ errors})}] \\ &= 1 - [(1 - .0121)^{15} + 15(.0121)(1 - .0121)^{14} + \binom{15}{2}(.0121)^2(1 - .0121)^{13}] \\ &= \underline{.0007} \end{aligned}$$

If we interleave the R/S code (interleave R/S symbols) then the burst correction goes up by factor of α where α = depth of interleaving. R/S codes are particularly well suited to be used for concatenation since the outer coder failure typically results in bursty error failure and the R/S codes are particularly well adapted to burst correction if implemented with binary constructed symbols.

APPENDIX D

AFFECT OF PSK DEMODULATOR CARRIER SLIP
ON DIFFERENTIAL ENCODED DATA WITH/WITHOUT INTERLEAVING

APPENDIX D

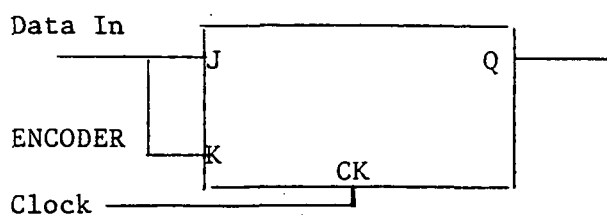
AFFECT OF PSK DEMODULATOR CARRIER SLIP

ON DIFFERENTIAL ENCODED DATA WITH/WITHOUT INTERLEAVING

Differential Encoding

Rule: Using page 1-9 of Reference 3, 1's cause change in level (Note, several possible rules to be used) 0's cause no change in level.

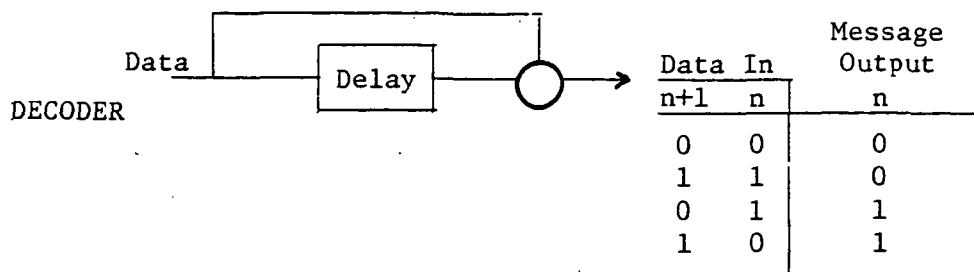
Use this with NRZ-M



$n+1^{\text{th}}$ Data In	n^{th} Output Equal
1	\bar{Q}_n
0	Q_n

Message in ... 1001000111001^{1st} ← assumed reference list in FF
That is $Q = 0$ assumed

Output 01110000010111



Recreated Message ^{1st} 10010000111001

Now let us invert the
bit stream so we
receive:

10001111 } 101110

The recreated message is: ^x 10010000111001
which contains one
error at the bit train inversion
point!)

Just for example's sake, let us put in data stream with 1 error

as: 01110000100110
and the output is: 1001000110101
xx

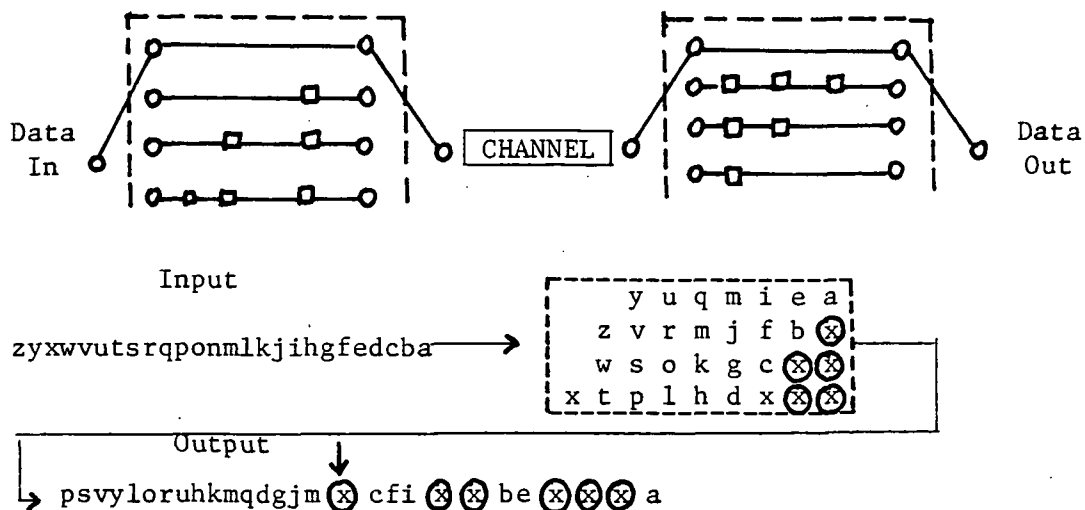
Note: Double errors out for random single errors input

Single errors out for single inversion in data stream.

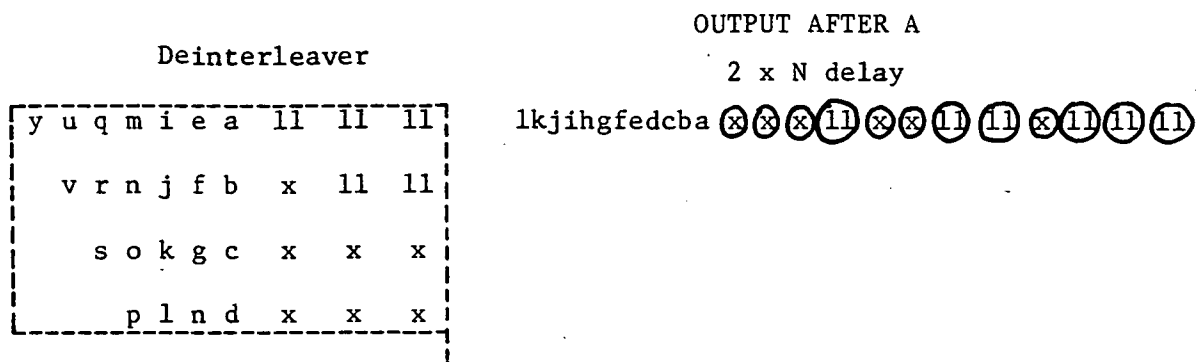
Now add an interleaver to the system.

Notes: (1) Each input symbol is spread a distance 4 from adjacent symbols.

(2) The first 2 x N symbols have spurious data.



First note that deinterleaving does work:



Now send a pattern and invert the bit stream:

..psvyloruhknqdg jm (x) cfi (x)(x) be (x)(x)(x) a = pattern with an inverted bit stream.

zyxwvutsrqponmlkjihgfedcba (x)(x)(x)(11)(x)(x)(11)(11)(x)(11)(11)(11) = received and deinterleaved data

$$\overbrace{\text{affected region}} = 2N - 2 = 10 \text{ bits}$$

INTERLEAVING HELPS WITH BURST ERRORS ON THE CHANNEL. BUT IF DIFFERENTIAL ENCODING/DECODING IS USED AND IF THE PSK DEMODULATOR EXHIBITS A CYCLE SLIP, INTERLEAVING RESULTS IN MANY ERRORS IN THE DEINTERLEAVED DATA STREAM.

APPENDIX E

MULTIPLE ACCESS SELF-INTERFERENCE

APPENDIX E

MULTIPLE ACCESS SELF-INTERFERENCE

1. General

This appendix defines the impact of Multiple Access (MA) system loading on self-interference. The impacts are defined in terms of probability of occurrence, increase in noise density, and decrease in achievable data rate.

2. MA Impact

A. The increase in noise density seen by a desired user is a function of the MA array gain in the direction of each interference source. Since the MA array gain in the direction of the desired user also varies with position, the increase in noise density caused by interference must be compared to the simultaneous gain in the direction of the desired user. The decrease in achievable data rate includes the effects of position of both the interference sources and the desired user, thereby, defining the impact of interference upon return link service.

B. Since the MA system uses PN code division multiple access, interference is spread in frequency by the PN rate resulting in an increase in noise density. The self-interference, therefore, impacts all users identically, in that high data rate and low data rate MA return links would experience the same increase in noise density. The following additional assumptions have been made for this analysis:

1. The minimum required MA G/T_s is - 1.3 dB/°K at edge ($\pm 13^\circ$) of FOV.
2. TDRSS provides a 1.0 - dB margin against MA self-interference.
3. TDRSS MA system margin is 0 dB.
4. Desired user margin is 0 dB in all cases.
5. No interference other than that resulting from MA users.
6. The desired user can appear randomly at any location with the $\pm 13^\circ$ FOV.

C. Tables D-1 through D-4 define the MA loading conditions for which self-interference was evaluated. The impacts of noise density increase and decrease in achievable data rate are computed for a hypothetical user coexisting with the interference sources defined by Tables D-1 through D-4. It is important to note that Interference Model No. 1A is a fully loaded MA system (10 users in view of each TDRS) while Model No. 1B is a worst-case in that all 20 users of a fully loaded MA system are assumed supported by one TDR spacecraft. The 10 additional models considered were fabricated to test the sensitivity of MA self-interference to user design margin and data rate distribution. Table 13 defines the self-interference impacts resulting from each interference model.

Table E-1. Interference Model No. 1A.

No. of Users	Altitude (km)	Inclination (degrees)	Data Rate (kb/sec)	Min EIRP (dBw)	User Margin (dB)	Assumed User EIRP (dBw)
2	300	30	10	16	3	19
2	300	90	10	16	3	19
2	300	30	25	21	3	24
1	300	90	40	22	3	25
2	300	30	40	22	3	25
1	33	30	50	23	3	26

Table E-2. Interference Model No. 1B.

No. of Users	Altitude (km)	Inclination (degrees)	Data Rate (kb/sec)	Min EIRP (dBw)	User Margin (dB)	Assumed User EIRP (dBw)
4	300	30	10	16	3	19
4	300	90	10	16	3	19
4	300	30	25	21	3	24
2	300	90	40	22	3	25
4	300	30	40	22	3	25
2	300	30	50	23	3	26

Table E-3. Interference Model No. 2A

No. of Users	Altitude (km)	Inclination (degrees)	Data Rate (kb/sec)	Min EIRP (dBW)	User Margin (dB)	Assumed User EIRP (dBW)
2	300	30	10	16	6	22
2	300	90	10	16	6	22
2	300	30	25	21	6	27
1	300	90	40	22	6	28
2	300	30	40	22	6	28
1	300	30	50	23	6	29

Table E-4. Interference Model No. 2B.

No. of Users	Altitude (km)	Inclination (degrees)	Data Rate (kb/sec)	Min EIRP (dBW)	User Margin (dB)	Assumed User EIRP (dBW)
4	300	30	10	16	6	22
4	300	90	10	16	6	22
4	300	30	25	21	6	27
2	300	90	40	22	6	28
4	300	30	40	22	6	28
2	300	30	50	23	6	29

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III. A REPORT CONCERNING PROPOSED ESTL END-TO-END TESTS AND POSSIBLE PROBLEMS ASSOCIATED WITH THE ENCODERS OF SPACE SHUTTLE

This section gives the historical perspective and rationale behind the ESTL Space Shuttle end-to-end tests that were conducted from the Houston JSC facility. Although this is a Space Shuttle program, the concatenated coding scheme using a convolutional encoder for the outer coder is a forerunner of the Space Telescope System. For this reason, it was felt important to monitor these tests in hopes that the experience gained would be valuable in the upcoming Space Telescope communication tests. This has definitely been the outcome.

ANALYSIS OF SPACE TELESCOPE DATA
COLLECTION SYSTEM

A Monthly Progress Report
Covering the Period
June 1, 1983 - July 1, 1983

Submitted to:

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812
Technical Monitor: Mr. Joe Thomas, EF-22
Technical Monitor: Mr. Glenn Parker, EB-33

By:

Mississippi State University
Engineering and Industrial Research Station
Department of Electrical Engineering
Mississippi State, Mississippi 39762

Principal Investigator: Frank Ingels
Contract No: NAS8-33570

Work Summary Covering the Period
(June 1, 1983 - July 1, 1983)

During this period a trip to White Sands Test Facility (WSTF) took place (actually the trip took place the last of May 1983 and was not reported in the May progress report.)

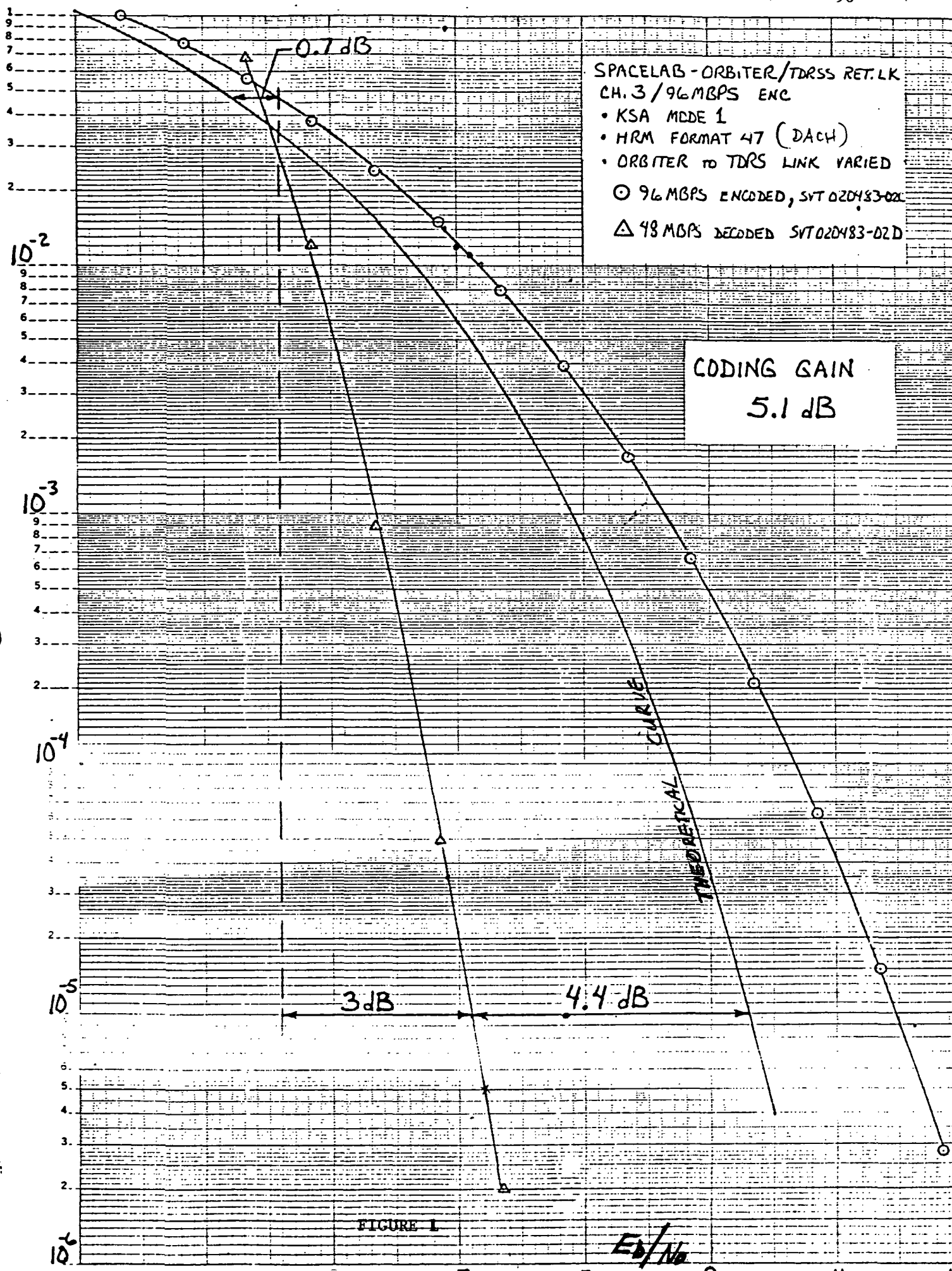
The purpose of this trip was to attend a conference concerning the Space Lab High Data Rate Link Tests to be performed at Johnson Space Flight Center (JSC) in the summer of 1983. A trip report was filed and Appendix I consists of this trip report.

Following the trip report several teleconferences were held concerning the tests that were run during the winter of 1983 period at JSC. These conversations were with Mr. John Follin of Harris Corporation (TDRSS Site Manager) and Mr. B. G. Smith of JSC. The purpose of these conversations was to determine once and for all whether or not there was an anomaly occurring during the JSC winter tests.

The possibilities of anomalies could be

- a) incorrectly operating convolutional decoders
- b) incorrectly conducted tests which starved
the receiver for signal power.

It was determined through discussions with Mr. Follin and Mr. Smith that the convolutional decoder set was correctly tested and that its performance was as theoretically expected. Figure 1 is a reproduction of the test results of the decoder during the JSC tests. From this curve it may be observed that the equivalent coding gain for a BER of 10^{-5} in E_b/N_0 SNR (dB) is approximately 6.8 dB as measured from



the curve in Figure 1. This is a variable factor depending on where the coding gain is measured. For instance the coding gain at a BER of 10^{-2} is roughly 2.5 dB. This illustrates that the 96 Mbps convolutionally encoded data is decoded to 48 Mbps with excellent performance by the decoder.

This leaves the second possibility that could have occurred, that of accidentally starving the receiver through use of an inline attenuator. Mr. B. G. Smith stated that not only was the SNR to the receiver an adjustable quantity but that the signal power level was also an adjustable quantity independently of the SNR adjustment. He stated that the tests were conducted with sufficient signal level such that the receiver was not run in a starved condition.

If one inspects the curves of Figure 1 it is obvious that operation at a 10^{-5} decoded BER corresponds to an encoded BER of roughly 1.1×10^{-2} . However a degradation of encoded BER to 1.2×10^{-2} corresponding to a reduction of the E_b/N_o SNR from 5.1 dB to 5.0 dB (a factor of .1 dB) yields a decoded BER of 2×10^{-5} and a further reduction of SNR from 5.0 dB to 4.9 dB yields a decoded BER of almost 4×10^{-5} and an encoded error rate of 1.4×10^{-2} .

From this data the exponential relationship of the decoded BER to the encoded BER at this operating point of the system is emphatically illustrated. As the SNR is increased by 1 or 2 dB the relationship becomes more or less a constant but down at low SNR values for encoded data the encoded BER curve is rapidly rolling off yielding large changes in decoded BER for small changes in encoded

BER. This phenomena results in dramatic changes in observed BER performance of the user decommutated channels as was noted during the tests.

The conclusion is that the JSC tests were properly conducted and that the test results are valid. We must hope the SNR link margin is as expected!

The On-Orbit tests scheduled for August 1983 are preceded by a closed loop test (Trailblazer Tests, JSC) scheduled for early July 1983. Discussion with Al English and Russ Coffey, both of NASA/MSFC resulted in agreement that it was not fruitful for this investigator to attend the July closed loop tests but rather to attend the On-Orbit tests.

A review of the Space Telescope Science Data error correcting coding system has been conducted in light of the Space Lab JSC test results. The system is fully analyzed and reported in both the 1980 and the 1982 interim final reports for this contract. The basic system seems to be immune to the error phenomena of the Space Lab systems but there is one item of possible concern. This item lies in the convolutional decoder/deinterleaver circuit. This portion of the circuit follows the bit synchronizer but precedes the frame synchronizer and Reed-Solomon decoder/deinterleaver. It is a critical location since any malfunction will potentially cause the frame synchronizer to lose lock or cause more errors that the Reed-Solomon decoder/deinterleaver can correct.

This circuit depends upon a synchronization loss signal which emulates from the convolutional decoder. This signal is not a frame synchronization signal nor a deinterleaver synchronization signal but rather a signal which indicates whether the proper three bits are being grouped together as a symbol. This signal is generated by averaging the branch error metrics over a fairly long span of symbols, however when the symbol synchronization is lost a potential 31 synchronizations states must be searched to reachieve symbol synchronization. The number of errors during this period will be phenomenal possibly lying within 6000 to 15000 bits. The Reed-Solomon decoder/deinterleaver can only correct 505 errors per encoded block of 16320 digits. As a result a symbol synchronization loss by the convolutional decoder/deinterleaver is tantamount ti disaster in so far as BER is concerned.

This potential problem was thoroughly discussed during a visit to Linkabit, San Diego, California with Mr. Steve Gardner of Linkabit.

Tests have been run at Linkabit during which a 5×10^{-2} random error input signal was delivered to the convolutional decoder/deinterleaver. The measured false synchronization loss rate was essentially zero. The 5×10^{-2} random error input occurs for about 4.5 dB input symbol to noise ratio. Reducing the input to 2.5 to 3.0 dB yields a false synchronization loss of lock signal about once every ten seconds for 3 Mbps input bit rate.

Once again if the link SNR is as specified the system should work fine.

APPENDIX

COPY OF WSTF

TRIP REPORT

MISSISSIPPI STATE UNIVERSITY
COLLEGE OF ENGINEERING



DEPARTMENT OF ELECTRICAL ENGINEERING
DRAWER EE
MISSISSIPPI STATE, MISSISSIPPI 39762
PHONE (601) 325-3912

May 25, 1983

Mr. Al English
EB33
MSFC, Alabama 35812

Dear Al,

Attached is a report concerning the Space Lab test meeting at White Sands May 23, 1983 - May 25, 1983. A good interchange took place between the ERND, ESA, JSC, KSFC, MSFC and WSTF personnel. In particular the Harris personnel at WSTF were very helpful and an afternoon discussion clarified many questions and brought to light the real crux of the JSC tests.

Am enclosing several copies for distribution to Jim, Gabe, Bernd and Russ.

Sincerely,


Frank Ingels

WSTF TRIP REPORT
May 23, 1983 to May 25, 1983

The main personnel involved in the meetings which took place concerning the Space Lab High Data Rate Link tests performed at JSC in the winter of 1983 were:

Mr. Malcolm Kershaw, ERNO
Mr. Fred Weijers, ESA
Mr. Rudy Selg, ESA (KSC)
Mr. A. C. English, MSFC
Mr. Dave Simmons, MKA (MSFC)
Mr. John L. Follin, Harris (TDRSS Site Manager)
Mr. Frank Ingels, MSU.

Many other people were in attendance but these activities concerned other details.

The main activities discussed in this report are:

1. Additional test procedures to be inserted in the Space Laboratory test procedure document being prepared for the On-Orbit tests. These tests are scheduled for early July 1983.
2. Determination of the actual phenomena observed in the HRDM tests at 48 Mbps during the JSC tests in Jan/Feb. 1983.
3. Discussion of possible remedies that could be employed should the On-Orbit tests prove unsatisfactory.

1. Test procedures were developed for the On-Orbit tests and added to the test procedure document.

- A. A first day test was requested so that a nominal operating condition Go/No-Go result could be obtained early in the KU band tests for 48 Mbps. Table 1 presents the material added, the test procedure step and the page of the test procedure document. This request will yield a Go/No-Go answer even if day 4 is not run.

In day 4 test procedures are conducted then some definitive operating/error conditions will be ascertained.

2. A discussion with personnel present at the JSC test and with Harris personnel of WSTF clarified some questions concerning the HRDM operation at those tests:

- A. The decoders at JSC appear to have been operating in proper order during the BER tests involving the HRDM. During the discussion a telephone call was made to JSC by a Harris personnel to confirm this point.
 - B. The JSC decoded test results do indicate that at a convolutional BER of 10^{-8} to the HRDM does operate in a satisfactory manner and that the experiment channel error rate is very low.

TABLE 1

TEST PROCEDURE REQUEST FOR KU 48 MBPS TEST

<u>Chronology</u>	<u>Action Item</u>
Day 1 Step 2A Page 164	1. Confirm Ch3 = 48 Mbps (HRM format 28).
Day 1 Setp 26 Page 170	1. Confirm HRDM configured for format 28 2. Verify - HRDM Sync lock - HRDM GMT display updating - HRDM Data Flow Status - HRDM Data Flow Status - (Exp Ch1 to 13, 15 I/O1, I/O2 HDRR) - Format ID is 28 (binary) 3. Record HRDM Sync Errors 4. Record BER an Experiment Channel E 5. Record POCC Frame Sync Percent Data Loss 6. Record BER an Experiment Channel F 7. POCC record data quality on Channels A, B and C.
* In addition the same test is requested on day 4 for 48 Mbps at 3 received SNR conditions:	
A). For convolutional decoded BER of 10^{-8} B). For condition A plus 3 db C). For best nominal link condition (0 attenuation).	

- C. The JSC test results indicate that operation at a convolutional decoder error rate of $5 \cdot 10^{-8}$ to the HRDM during the JSC tests resulted in an apparent unacceptable error rate in the experimenter channel decommutated data outputs.

This steeply degrading performance apparently arises from bursty bit errors emulating from the convolutional decoders. This creates a channel error condition which is in direct contradiction to the design guidelines of the HRM/HRDM.

- D. The method of simulating the RF channel during the JSC tests may be creating a bursty error channel. This procedure used a waveguide attenuator in the coupling from the transmitter to the receiver. As shown in Figure 1 this reduces the signal power to effect a lower signal-to-noise ratio. If the signal power is reduced to a level below that required for solid PSK demodulation (assuming a COSTA'S style receiver) then occasional cycle slips or phase reversals would occur which would create bursty errors to the convolutional decoders. This in turn would look like an average error rate to the convolutional decoders of 10^{-5} but in fact would degrade the performance of the decoders significantly. Operators would naturally assume that the attenuated signal level had approximated a random error channel but this would not be the case.

The best method as illustrated in Figure 1 would add noise to an established minimum received signal power. This ensures that the demodulator in the receiver is operating above its threshold and that only channel errors are passed on to the convolutional decoder.

- E. The convolutional decoder operating characteristics are documented in Figure 2. This decoder should yield an average output error rates shown in Table 2 for the indicated random input error rates.

The discussions of the test results at JSC indicate that with a convolutional decoder input (link) error rate of approximately 10^{-5} (point A error rate illustrated in Figure 3) during testing the convolutional decoder output error rate (point B, Figure 3) was approximately $5 \cdot 10^{-8}$! This is not as expected from either theoretical predictions or from experimental testing of the actual decoders!

When I pointed this out to the Harris personnel at WSTF they immediately agreed that either the decoders at JSC were not operating properly during the test or the input errors to the convolutional decoders was not random!

AN OUTPUT ERROR RATE AT POINT B, FIGURE 3, OF LESS THAN 10^{-10} IS EXPECTED IF THE INPUT ERROR RATE IS RANDOM ERRORS AT 10^{-5} AVERAGE BER.

TABLE 2

<u>Average Input Error Rate</u> (Random Errors) (Randomly Spaced Input Errors)	<u>Average Output Error Rate</u> (Short Bursts Averaging to a BER)	<u>Output Error Event Rate</u>
10^{-2}	$5 \cdot 10^{-5}$	$7.2 \cdot 10^{-6}$
10^{-3}	$6 \cdot 10^{-8}$	$8.6 \cdot 10^{-9}$
10^{-4}	less than 10^{-9}	$1.5 \cdot 10^{-10}$
10^{-5}	less than 10^{-10}	$1.5 \cdot 10^{-11}$

NOTE: Output errors will occur in short bursts of approximately 7 errors or perhaps multiples of 7 errors. The average output error rate will be as indicated and has been well documented in testing. THUS AN AVERAGE OUTPUT ERROR RATE OF: $5 \cdot 10^{-5}$ would appear as error events consisting of clumps of errors at an error event occurrence rate of approximately $7.2 \cdot 10^{-6}$, $6 \cdot 10^{-8}$ would appear as an error event occurrence rate of $8.6 \cdot 10^{-9}$ etc.

AN OUTPUT ERROR RATE AT POINT B, FIGURE 3, OF 10^{-8} SHOULD RESULT FROM AN AVERAGE RANDOM INPUT ERROR RATE AT POINT A, FIGURE 3, OF $1.5 \cdot 10^{-3}$.

Harris personnel at WSTF stated they would test the decoders at 10^{-3} , 10^{-4} , 10^{-5} average random input error rates to confirm the operational points of Table 2. (Mr. John Follin, TDRSS Site Manager, (505+524-8583)).

It is very tempting to assume the JSC test procedure introduced some anomaly that created bursty errors to the convolutional decoders. This situation should not result under actual link operations.

- F. It is instructive to present a simplified experimenter channel error rate analysis to illustrate the desirable required error rate from the convolutional decoders. Since the experimenter channel error rate depends upon the experimenters format some assumed formats will be used for examples.

ASSUMPTIONS: 1. Errors are emanated from the convolutional decoders in bursts of 7 spaced 5 bits apart which yields the average error event rates in Table 2.

2. Experimental channel format

Case A:	1000	bits/experimenter frame
	1	experimenter words/HRDM line
	62.5	HRDM lines/experimenter frame
Case B:	1000	bits/experimenter frame
	3	experimenter words/HRDM line
	20.8	HRDM lines/experimenter frame

Assuming an error event rate (EER) of $1.5 \cdot 10^{-10}$ (corresponding to an average output error rate of 10^{-9} from the convolutional decoders and an average link error rate to the convolutional decoders of 10^{-4} the probability of a BCH word being hit with 4 or more errors would be approximately

$$\text{EER} \times \frac{2}{12} \times \frac{4}{7} = .0953\text{EER}$$

If we assume that the experimenter's frame synchronizer detector will take 6 frames to recognize synchronization loss and to establish a new synchronization lock then the experimenter loses 6 frames of data for every BCH word hit of 4 or more errors or at a rate of .0953EER.

Thus the experimenter loses 6000 bits at a rate of .0953EER per loss occurrence.

The average number of experimenters frames between loss occurrences is (EFBLO).

$$\text{EFBLO} = \frac{1}{(.0953\text{EER})(\text{HRDM Lines/Experimenter Frame})}$$

The experimenter average error loss is thus (EEL)

$$\text{EEL} = \frac{6000}{\text{EFBLO}}$$

For case A we have

$$\begin{aligned} \text{EEL} &= 6000(.0953\text{EER})(\text{HRDM Lines/Experimenter Frame}) \\ &= 6000(.0953 \times 1.5 \cdot 10^{-10})(62.5) = 5.36 \times 10^{-6}(\text{BER}) \end{aligned}$$

Table 3 depicts the estimated error rates.

LINK ERROR RATE (POINT A, FIGURE 3)	CONVOLUTIONAL DECODER ERROR RATE (POINT B, FIGURE 3)	EXPERIMENTER FRAME LOSS RATE FRAME ERROR RATE (FER)	EXPERIMENTER ERROR RATE BER
--	---	--	--------------------------------

CASE A: 1000 bits/experimenter frame; 1 word/HRDM line; 62.5 HRDM lines/experimenter frame

10^{-3} BER	6×10^{-8} BER ($8.6 \cdot 10^{-9}$ EER)	3.1×10^{-7} FER	3.1×10^{-4} BER
10^{-4} BER	10^{-9} BER ($1.5 \cdot 10^{-10}$ EER)	5.36×10^{-9} FER	5.36×10^{-6} BER
10^{-5} BER	10^{-10} BER ($1.5 \cdot 10^{-11}$ EER)	5.36×10^{-10} FER	6.36×10^{-7} BER

CASE B: 1000 bits/experimenter frame; 3 words/HRDM line; 20.8 HRDM lines/experimenters frame

10^{-3} BER	$6 \cdot 10^{-8}$ BER ($8.6 \cdot 10^{-9}$ EER)	1.1×10^{-7} FER	1.1×10^{-4} BER
10^{-4} BER	10^{-9} BER ($1.5 \cdot 10^{-10}$ EER)	1.78×10^{-9} FER	1.78×10^{-6} BER
10^{-5} BER	10^{-10} BER ($1.5 \cdot 10^{-11}$ EER)	1.78×10^{-10} FER	1.78×10^{-7} BER

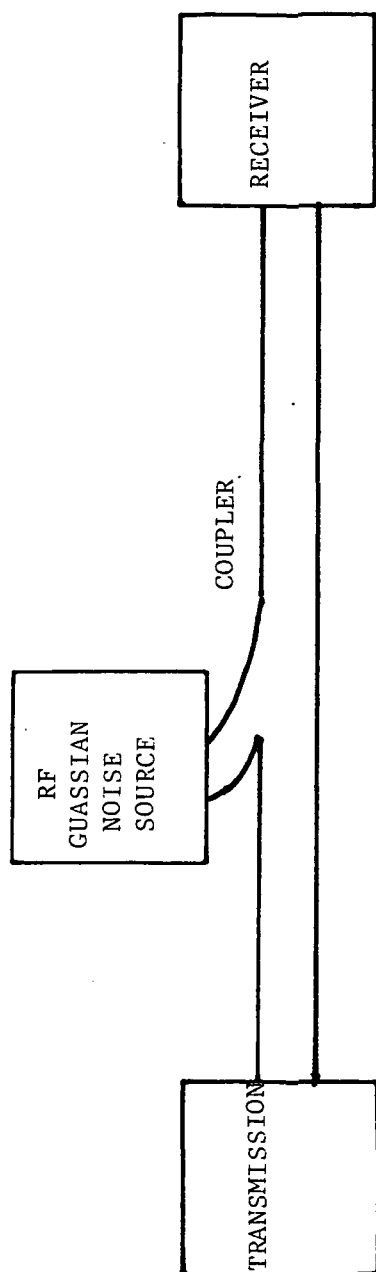
G. The Harris personnel at WSTF are certain that the link margin will be 8 to 10 db above that required to yield 85.3 dbm/Hz at the WSTF receiver. 85.3 dbm/Hz should provide less than 10^{-9} error rate out of the convolutional decoders. Thus the system should perform in a very low error environment. If we assume that 8 db excess link margin exists; 1 extra db of margin would guarantee less than 10^{-10} error rate out of the convolutional decoders (corresponding to an EER of $1.4 \cdot 10^{-11}$) yielding an average experimenter bit error rate of approximately $5 \cdot 10^{-7}$ BER.

Naturally any extra margin will reduce the BER at approximately 1 order of magnitude per db extra margin.

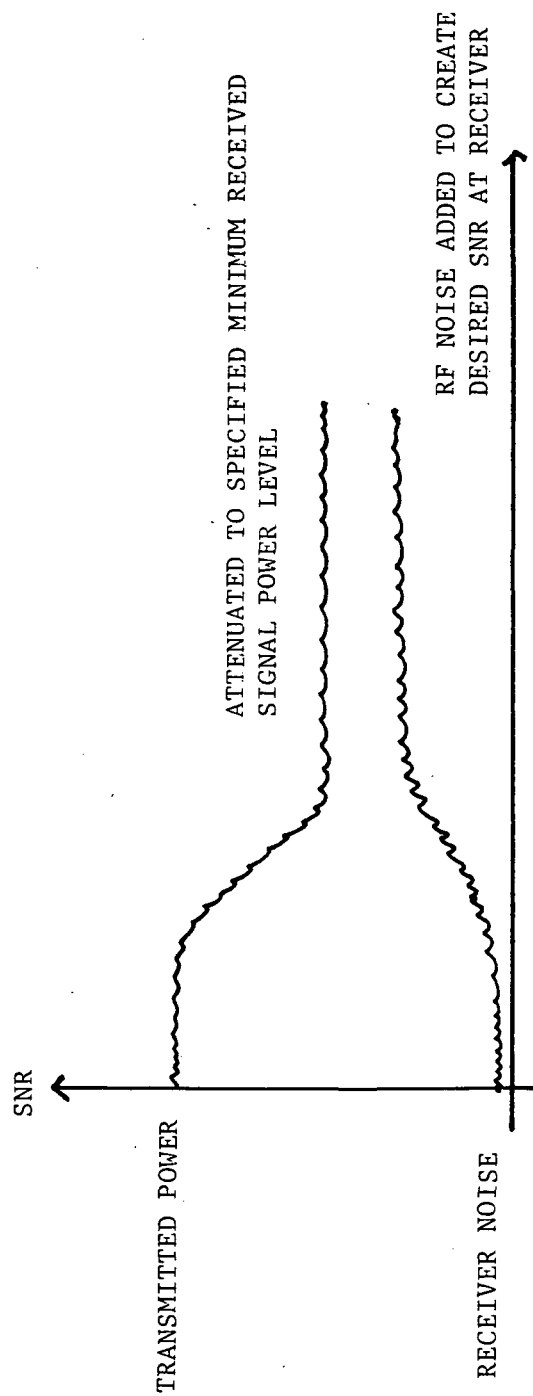
THE BOTTOM LINE CONCLUSION IS THE 48 Mbps LINK SHOULD PERFORM AS DESIRED.

3. Possible remedies that could be employed to increase the Space Lab 58 Mbps link have been discussed. The simplest thing to do which should yield a definite improvement in the system performance (By perhaps an order of magnitude in BER reduction) would be to split the BCH word into two locations in a HRDM line. Thus instead of having the BCH word occupy words 11 and 12 in a line, words 5 and 12 would contain the BCH word.

Perhaps this won't be necessary but it would be a definite possibility and the first thing recommended if On-Orbit tests indicate the need for further action.



(a)



(b)

FIGURE 1

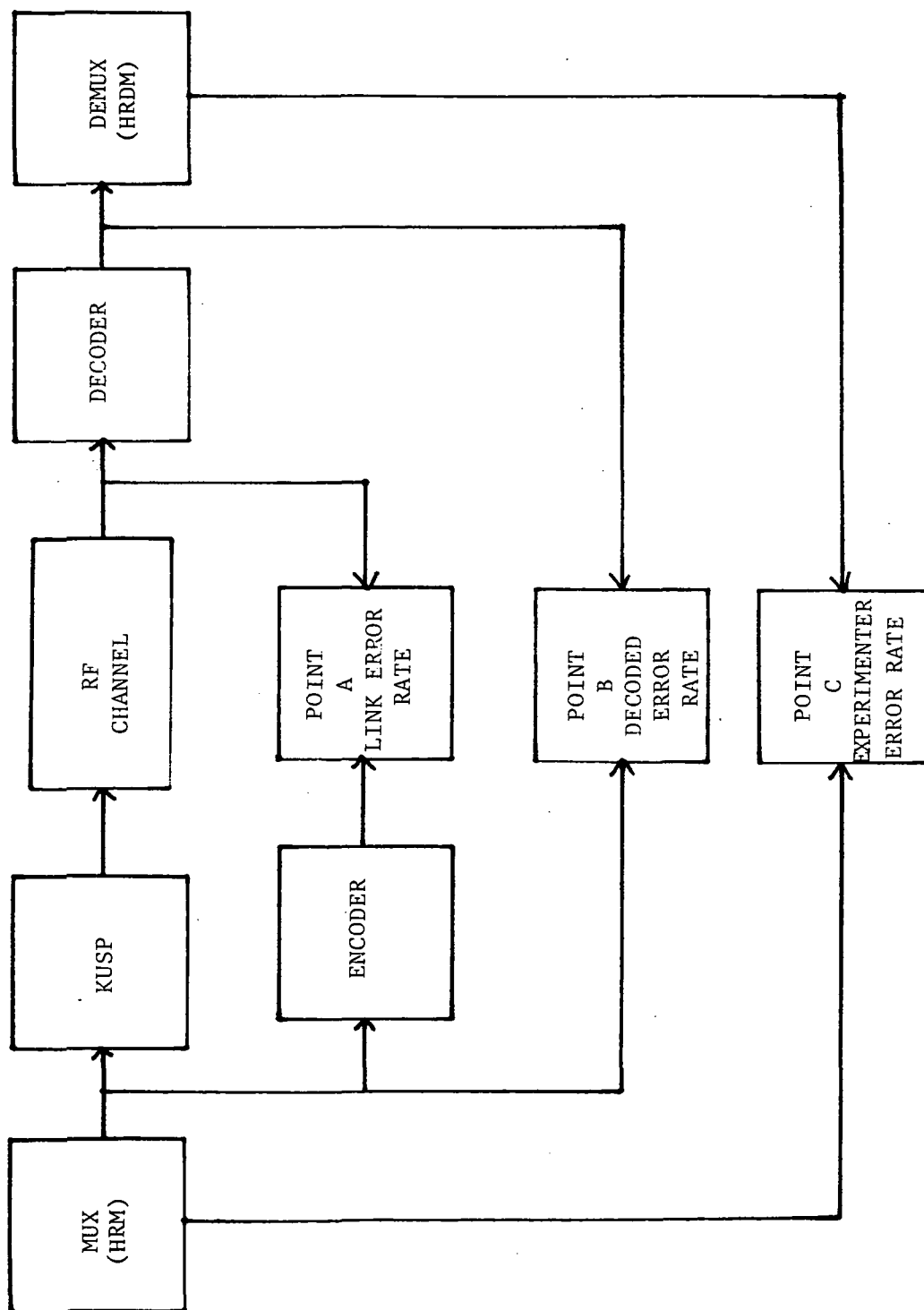


FIGURE 3

IV. A REPORT ON THE ESTL END-TO-END TESTS

This section describes the ESTL end-to-end tests on the Space Shuttle Communication Link. The most important outcome is the harsh reality of how a concatenated coding system with convolutional coding for the outer codes will perform. The system is in essence a go-no-go system with respect to received Signal-to-Noise ratio. This comes about from the bursty output error nature of a Viterbi decoder when faced with more errors than it can correct.

The result for Space Shuttle is very dramatic. For Space Telescope, there is some help in that the inside code is Reed Solomon rather than BCH. However, it was clearly demonstrated during these tests that false sync lock loss by the Viterbi decoder would be disastrous for the Space Telescope communication links.

ANALYSIS OF SPACE TELESCOPE DATA
COLLECTION SYSTEM

A Monthly Progress Report
Covering the Period
July 1983 - September 1983

Submitted to:

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812
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Contract No: NAS8-33570

ANALYSIS OF SPACE TELESCOPE DATA
COLLECTION SYSTEM

ESTL CLOSED LOOP TDRS TESTS; JSC; AUGUST 21-25, 1983

The closed loop end-to-end tests held at JSC during August 21-25, 1983 were attended by this investigator. The main objective was to determine the error mechanism of the Convolutional Decoder/HRDM/Science User data system. The characterization of this error mechanism is necessary to allow a potential fix to be determined in case the link margin from the space vehicle to TDRS to White Sands, NM to the POCC facility is not sufficient to provide a Science Data output that is sufficiently error free.

As it developed the end-to-end tests illustrated a solid channel with sufficient link margin to operate essentially error free in so far as the Convolutional Decoder/HRDM/Science User data system is concerned. Characterization of the error mechanism which develops for lower link SNR was accomplished however and it is documented here for possible further need.

The problem arises due to the bursty nature of the error output from the convolutional decoder in conjunction with a BCH encoded valid/invalid fill word in the data format. An error multiplication effect occurs when the BCH decoder is unable to decode an encoded word due to too many errors occurring from the convolutional decoder. This results in added or deleted words in the science user decommutated data channel which creates a loss of synchronization for that

particular channel. The resulting data loss to that specific science data channel is severe since decommutated channel syncs must be reestablished before data is again received correctly.

Original ESTL High Data Rate closed loop tests run in February - March 1983 at JSC had demonstrated this problem and some cursory data taken at that test indicated error bursts of 7 bits or multiples of 7 bits spaced 5 bits apart. The error rate for the decommutated channels seemed "to fall apart" at about a 10^{-8} decoded BER. (Decoded BER refers to the error rate out of the convolutional decoder as opposed to an encoded error rate which is the RF channel error rate input to the convolutional deinterleaver (decoder))

If the link margin is sufficiently strong to provide an encoder BER of 10^{-5} to the convolutional deinterleaver/decoder then the system will run almost error free. However it was felt necessary to characterize this error phenomena so that a possible method of overcoming the problem could be determined in case the link margin is not sufficient to allow a satisfactory operational science user data BER out of the decommutated channels.

The characterization was accomplished by inspecting a typical RF channel encoded BER pattern for an established BER encoded of $5 \cdot 10^{-2}$ BER. This encoded error rate corresponds to a decoded error rate of 10^{-5} BER which is then passed to the HRDM.

It should be noted at this point that the specifications for the convolutional decoder equipment apparently read "...that the decoded BER shall be 10^{-5} BER.." and the specifications for the HRDM BCH

decoder reads in effect "... shall produce a BCH decoding failure rate of 10^{-11} for a random input BER 10^{-4} ...". These two specifications are quite different!

After determining that the encoded channel BER of $5 \cdot 10^{-2}$ did in essence consist of randomly spaced errors, error patterns out of the convolutional decoder were recorded and the average BCH decoding failures were statistically estimated as a function of the burst lengths for an established decoded error rate of 10^{-5} to the HRDM.

Figure 1 illustrates a typical encoded channel error pattern. The randomly spaced errors are evident as is the clustering effect of the convolutional deinterleaver which groups every fifth bit to specific decoder.

The typical error patterns coming from the convolutional decoders and input to the HRDM are illustrated in Figure 2. These error patterns were obtained by using a Logic analyzer to store the data patterns. The enhanced bits under the decoded pattern are the erroneous bits. The results indicate more than one of the five parallel convolutional decoders are outputting errors at the same time. This is as one would expect. The errors are more frequent and random than the previously alluded 7 bit or 7 bit multiple error patterns spaced 5 bits apart which would indicate only one decoder emitting errors at a time. Furthermore the errors span 2,3,4,5, and 6 data words (and more on occasion) often with more than 3 errors for a 32 bit word combination. Thus one may observe why the BCH decoder in the HRDM has exhibited problems under these circumstances.

Having determined the typical error patterns being submitted to the HRDM under a decoded error rate of 10^{-5} the statistical distribution of uncorrectable BCH patterns versus error events in the HRDM input data stream was desired. Only this information could lead to a scientifically sound fix of the problem, if it is deemed necessary to provide a fix. Furthermore, it is always desirable to understand an unexpected phenomena so that it may be no longer unexpected nor a mystery.

A series of error events input to the HRDM were recorded with the operating point of a decoded error rate of 10^{-5} BER. Table 1 presents this small statistical sample. One observes that the average number of errors in any single error event is 42.5 bits long and overlaps an average of 3.5 words per burst. (A word is a 16 bit length.) The number of errors per burst varies but the longer bursts typically contain many more errors.

Since the parameter of interest is the number of word pairs (adjacent 16 bit words) that contain more than 3 errors and hence would not be correctable by the BCH decoder, the data does not directly inform one of the desired information. Figure 3 presents a plot of the percentage of uncorrectable word pairs versus the burst length in words (originally proposed by Mr. Malcolm D. Kershaw of ERNO). This plot illustrates the fact that a break in the curve occurs for a burst length of 4-5 words in length. (The statistical sample of 1276 bits (80 words) containing error events is somewhat short but still the sample should be fairly typical).

Approximately 92 percent of the uncorrectable error patterns occur for burst lengths of two or more words. This illustrates why the HRD/HRDM modification which separated the BCH word by two data words was not effective in reducing the science user decommutated data error rate. Only 8 additional percent of error events were correctable as indicated by the measured data.

Approximately 33 percent of the uncorrectable error events occurred in burst lengths of over 5 words. In 30 recorded error events no burst lengths of over 8 words were noted, however this does not preclude such longer burst lengths from occurring.

It is noted however that if the BCH word were separated by 10 or more words the majority by far of the error events would be correctable. At least an order of magnitude improvement would be expected, probably several orders of magnitude improvement would be experienced. This would result in a satisfactory science user decommutated error rate.

There are other considerations involved in separating the BCH word even by so simple a technique as placing one BCH 16 bit segment on one line and the second BCH 16 bit segment on the next line, thus effecting a 12 word separation. First the HRDM is demonstrating some rather critical internal timing problems as more and more operating experience is gained at JSC and at White Sands. These critical timing areas would be a definite factor in any attempt to separate the BCH word and any such attempt must be very thoroughly tested.

Secondly it is important to realize that the ESTL High Data Date closed loop test run at JSC during February-March 1983 have demonstrated that the 48 MBPS HRM-HRDM system falls apart only 2 dB above the signal level for which the total system experiences a crash (probably due to the bit synchronizer dropping out). Thus any large amount of time and money spent on increasing the tolerance of the BCH word to decoded error patterns would buy at most 2 dB effective increase in performance.

Summarizing:

1. It seems apparent from the ESTL closed loop JSC-TDRS-WS-DOMSAT-JSC tests of August 21-25, 1983 that sufficient link margins are achieved to allow essentially error free operation in so far as the science user decommutated data channel is concerned.
2. Characterization of the error phenomena experienced during the JSC closed loop tests of February - March 1983 was successful.
3. A scientifically sound approach to increase the tolerance of the BCH decoder in the HRDM to error events from the convolutional decoder is in fact possible and is fairly simple. The simplest approach would be a separation of the BCH word 16 bit segments by one line.

4. Due to critical HRDM timing areas any modification in BCH format must be very thoroughly tested.
5. From earlier ESTL closed loop system tests it appears that no more than 2 dB effective systems performance gain can be achieved by making the HRD-HRDM work in a flawless mode. This conclusion is due to the test results that indicate overall system occurs 2 dB below the HRDM BCH decoding failure point. Thus any costly or time consuming changes should be weighed against real necessity versus performance gain versus cost/time effects.

98 MBPS RF DATA STREAM, TYPICAL ERROR BURST (100 BITS SAMPLE)
(RF CHANNEL ERROR RATE ESTABLISHED AT $5 \cdot 10^{-2}$ BER)

DATA ERRORS	0111 0100 0001 1001 0001 0111 0000 0101 1101 0101 0011 0100
	1 1 2 3
	X X X X X
ERRORS DATA	0111 0100 0101 1101 0001 0111 0100 0101 1101 0001 0111 0100
DATA +	0101 1101 0011 0111 0100 0101 1101 0001 0111 0100 1101 0001
ERRORS	5 5 X
DATA	0101 1101 0001 0111 0100 0101 1101 0001 0111 0100 1101 0000

The numbers above the errors (indicated by an x) depict the decoders to which the errors would be sent after the deinterleaving of the RF channel bit stream. In this 100 bit sample the encoded (RF channel) BER was set by attenuator to $5 \cdot 10^{-2}$ BER corresponding to a decoded (convolutional output error rate) error rate of 10^{-5} . There are 7 errors in the 100 bits with random spacing (that is no strong tendency to cluster). After deinterleaving decoder 1 would receive 2 adjacent errors, decoder 2 would receive 1 error, decoder 3 would receive 1 error, decoder 4 would receive 1 error and decoder 5 would receive 2 errors spaced 6 bits apart.

Figure 1. Typical Error Burst of RF Channel Encoded Data

CLOSED LOOP JSC TEST 21 AUGUST 1983
Error Rate Estimated From Sync Error Rate

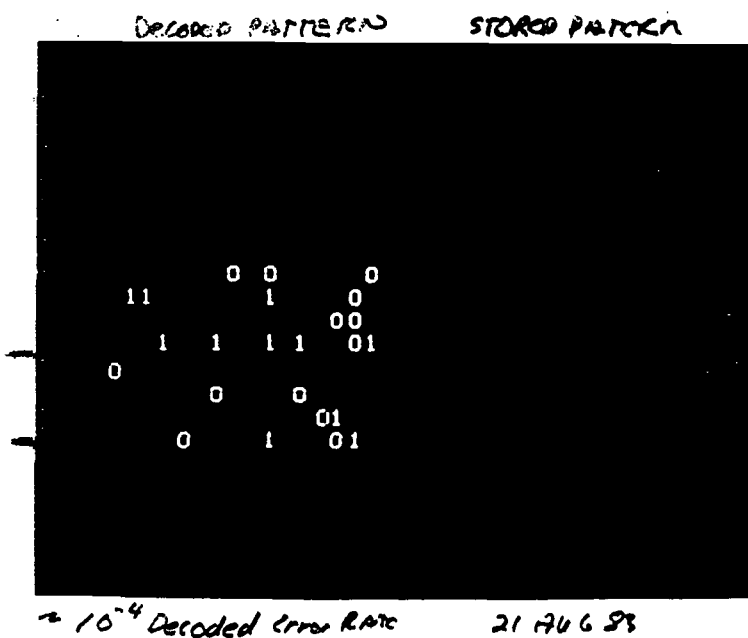
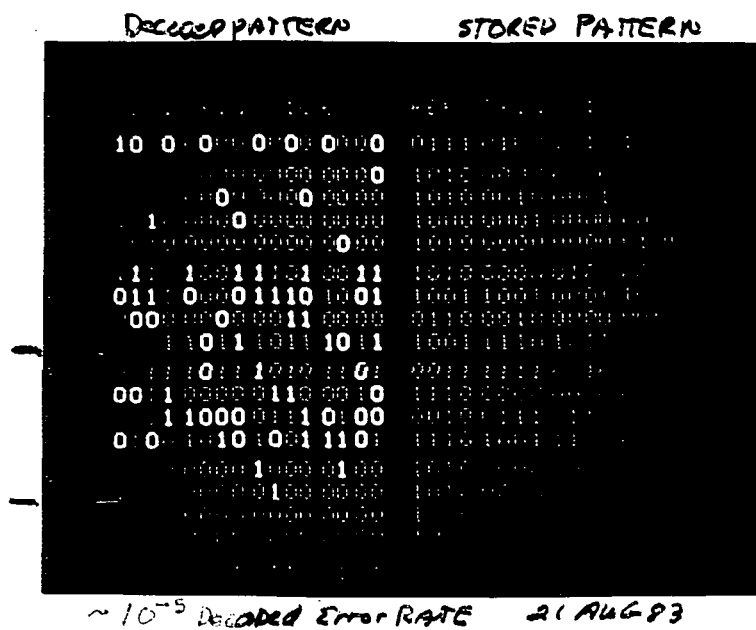


Figure 2. Typical Error Patterns For Decoded Data

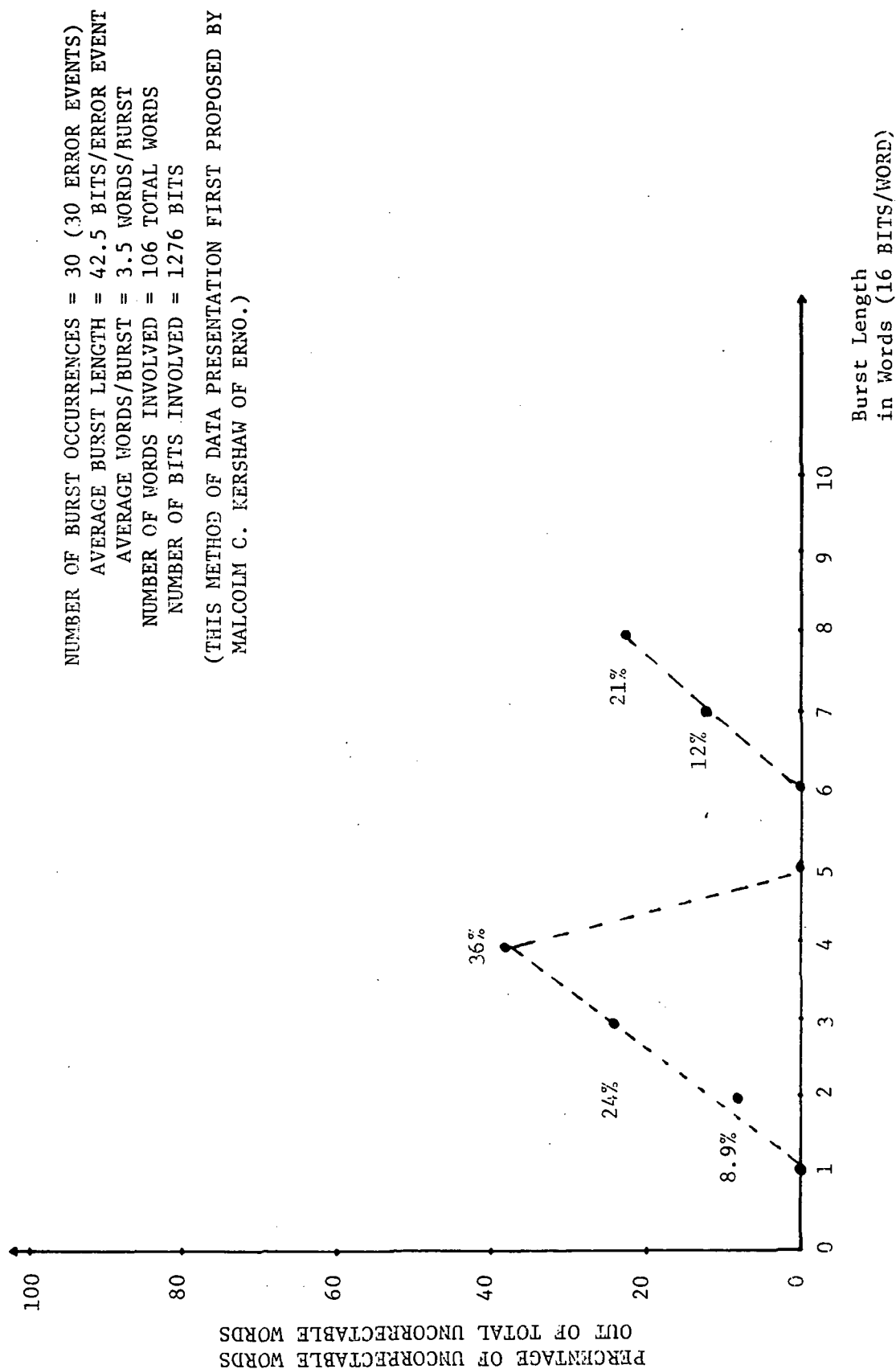


Figure 3. The Percentage of Uncorrectable Word Pairs Versus Burst Length

TABLE 1

Data Collected: 22 August 1983.
 Convolutional Decoded Error Rate Set with Attenuator
 to 10^{-5} Average BER. Every Time an Error Occurs in
 Sync Word Logic Analyzer Contents Recorded. 16 Bits/
 Word.

<u>ERROR EVENT</u>	<u>ERROR BLOCK LENGTH (BITS/BURST)</u>	<u>NUMBER OF WORDS WORDS/BURST</u>	<u>NUMBER OF UNCORRECTABLE ERROR PAIRS IN BURSTS</u>
1	86	7	2
2	101	7	1
3	36	3	0
4	61	4	1
5	11	1	0
6	86	6	0
7	26	3	2
8	31	3	1
9	36	3	0
10	21	2	0
11	61	4	0
12	26	2	1
13	41	4	2
14	36	4	2
15	15	2	0
16	111	8	0
17	1	1	0
18	36	3	2
19	6	2	0
20	31	3	1
21	56	4	0
22	16	2	0
23	106	8	5
24	15	1	0
25	86	6	0
26	46	4	2
27	46	4	2
28	15	2	0
29	26	2	1
30	5	1	0
	<u>1276</u> TOTAL BITS	<u>106</u> TOTAL WORDS	<u>25</u> TOTAL PAIRS UNCORRECTABLE

V. MEMORANDUM CONCERNING SPACE TELESCOPE VERIFICATION
REQUIREMENTS AND SPECIFICATION DOCUMENT (VRSD)

This section contains a discussion of the VRSD for Space Telescope and a few recommendations for those sections of the VRSD that apply in particular to the Space Telescope data and communication system. These suggestions are based on some of the experience gained in the ESTL end-to-end tests of the Space Shuttle communication system with its concatenated coding systems.



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May 18, 1984

TO: Glenn Parker
EB-33
MSFC, AL. 35812

FROM: F. M. Ingels, M.S.U.

SUBJECT: ST VERIFICATION REQUIREMENTS AND SPECIFICATION DOCUMENT (VRSD),
SAV-1020A, APPENDIX D, JANUARY 5, 1984. [Note: The next
update of this Appendix will be published as SAV-1024.]

Although this document is stated in the Forward to include the general requirements for ST Systems End-to End Testing including mission simulation and STOCC interface, it is most appropriate to specify some specific generalities concerning the overall science data link which includes the R-S encoder/interleaver, the convolutional encoder/interleaver and PN cover sequence. The specific generalities in question concern the determination of the characteristics of the Viterbi/PN cover sequence decoder synchronization lock and the R-S decoder/deinterleaver synchronization and of course the error characteristics of the end-to-end science data path.

To ensure that these parameters are tested under a variety of Signal-to-Noise (SNR) conditions, established by appropriate Energy Per bit to-Noise (E_b/N_o) levels, it is suggested that several insertions be added to the ST VRSD.

On page D-9 it is stated at the end of section 3.2 (beginning page D-8), Test Constraints and Considerations, that a method of comparing data as it is processed by SATS, WF/PC GSE, or the VAPGS with the data at the STOC or ST Sci will be developed and used post test. From this statement it is implied that a science data stream before transmission is either stored or known and can be compared with the decoded/deinterleaved version; nevertheless, it is desirable to clarify this point. Thus it is suggested that the following statement be added at the end of section 3.2:

A predetermined data stream sequence format with a known data sequence will be used to test the science data R-S and Convolutional encoders/interleavers, PN cover sequence, PN cover sequence/Viterbi decoder/deinterleaver and R-S decoder/deinterleaver. The purpose of this will be to aid in determining the accuracy of the overall error protection encoding procedure under a variety of SNR (E_b/N_o) conditions varying from excellent SNR to very poor SNR in the phase three verifications.

To ensure a thorough testing of the science data link from start to finish and to uncover any potential system design faults it is recommended that a variety of SNR (E_b/N_o) levels be used during the testing and that deep fades be simulated during testing. This will allow the data system characteristics to be determined before actual launch. To achieve this testing it will be necessary to:

- A) Record the generated data stream
- B) Record the received decoded/deinterleaved data stream

- C) Record the E_b/N_0 level and the duration and depth of simulated deep fades created by possible RFI.
- D) Monitor and record any false synchronization Lock Loss conditions which may be exhibited by the Viterbi/PN sequence decoder/deinterleaver and/or by the R-S decoder deinterleaver.
- E) Determine the effective bit error rate by comparing the generated data stream against the received decoded/deinterleaved data stream and counting the disagreements.

Naturally the above cannot be accomplished by hand techniques; hence it is necessary for those in charge of the testing to consider these needs now and to accumulate necessary logic analyzers, counters, data sequence generators and synchronizers.

It is recommended that the following statement be added in section 3.3.1.3, Phase Three Verifications on page D-11 following the first bullet (Ability of the ST to communicate with POCC and DCF via TDRSS MA and SSA Links):

In particular the end-to-end science data bit error rate will be monitored and determined under a variety (at least four) of SNR conditions including excellent, acceptable and minimum SNR levels and a simulated RFI fade (or interference conditions simulated by addition of random phase and amplitude RF energy). Determination of the error characteristics is deemed important. Specifically the bit error rate, randomness, burst frequency and length of the

error bursts should be documented. In addition any false synchronization lock loss by the Viterbi/PN decoder/deinterleaver or by the R-S decoder/deinterleaver should be documented.

If these statements are added, it is my belief that not only will the tests uncover any system design weakness but also give a test bed performance to use as a guideline for exercising the system during an actual mission under RFI conditions.